VERTICAL CURRENT STRUCTURE IN THE GREAT LAKES

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INTRODUCTION

The specific aims of this research program were to study the transient characteristics of the vertical profile of horizontal currents in the Great Lakes under the influence of the wind stress. Data were obtained from buoy Station 8 (Fig. 1) established by the U. S. Public Health Service Great Lakes-Illinois River Basins Project. These data consisted of surface wind measurements, and water currents at 10, 15, 22, 30, 66 and 90 meters depth. The method of approach to the problem was to use instantaneous values of the water currents and surface winds (read from the buoy station data) as initial conditions, and then to use the subsequent wind record as input to a computer program for the calculation of the water current behavior as a transient function of the wind stress. The calculated currents were to be compared with the observed currents to establish a range of values for the energy exchange coefficients, such as the eddy viscosity, drag coefficient, and surface energy loss coefficient.

The limited amount of information from marine work has indicated that the models of Ekman (1905), Fjeldstad (1930), Hidaka (1933), and Welander (1957) would give a reasonable prediction of the local steady-state currents as established by the wind field. These same models demonstrated agreement with the observed Great Lakes currents as indicated by Ayers et al. (1958) and Noble (1965a). Because of the experimental problems and lack of appropriate instumentation, all of the above results were based on the "steady state" currents as were measured in the field experiments. As indicated by Noble (1965a), the steady-state predictions appeared to have as much validity in the Great Lakes as had been previously documented in marine research.

The original proposal was therefore designed as a straightforward one-year effort to take advantage of the instrumentation facilities available in the Great Lakes. The continuous current data from Station 8 provided a unique opportunity to compare the transient characteristics of tide-free current profile with the predictions of the theoretical models. It was assumed that each period of data to be examined would yield empirical values for the exchange parameters, and that the range of values of these parameters would be useful for an understanding of the variability of the transient dynamics of the current structure, and to develop a specific current prediction capability in the Great Lakes. It was further felt that the simplified experimental conditions existing in the Great Lakes would provide for a means of evaluation of the exchange parameters to be applied in experiments conducted by the marine institutions in tidal waters.

Fig. 1. Lake Michigan.

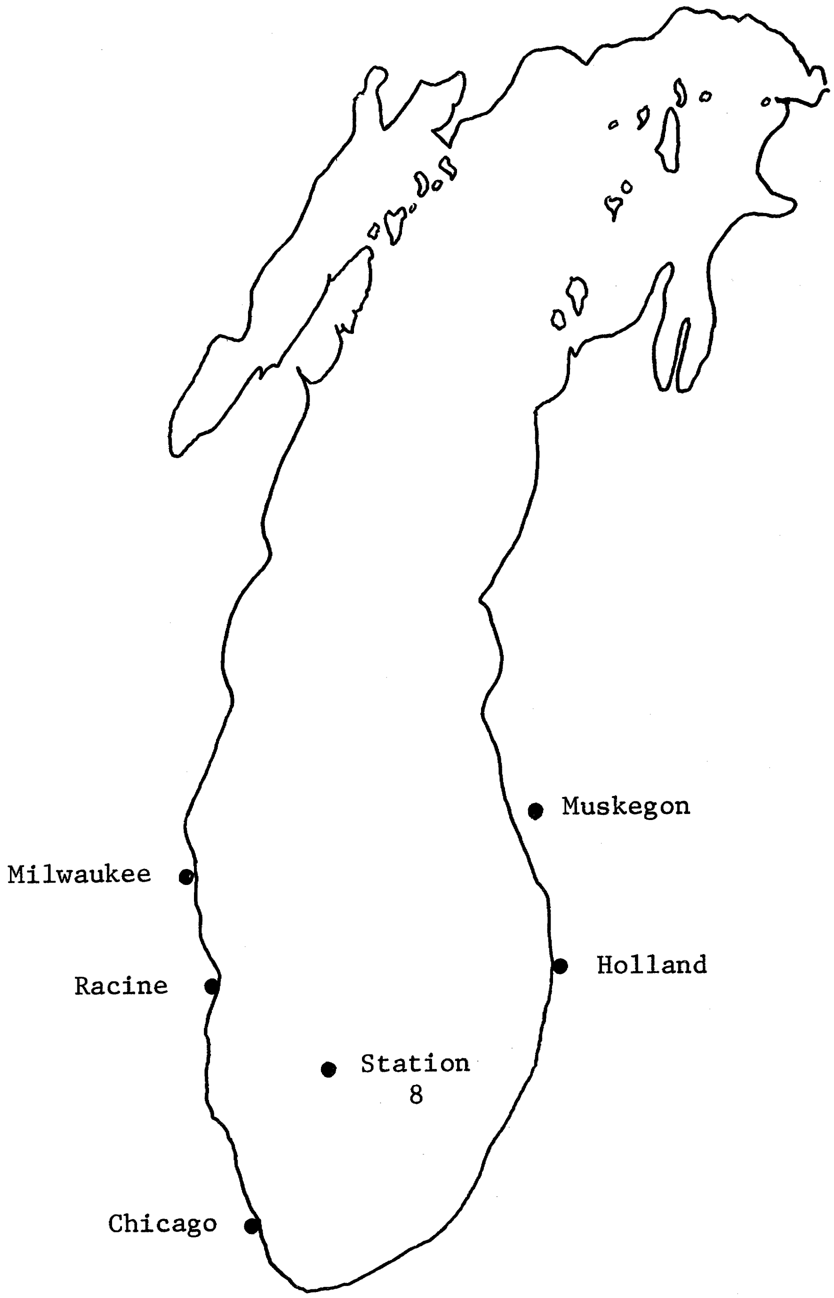


Fig. 1. Lake Michigan.

As will be demonstrated below, the attemps at using the Ekman-type models for the synthesis of the observed transient current structure were not successful.

RESULTS FROM EKMAN-TYPE MODEL

The equations used to calculate the Ekman-type vertical current structure from the local winds are extended from the work of Ekman (1905), Fjeldstad (1930), Hidaka (1933), and Welander (1957). They may be written as:

$$\frac{\partial u}{\partial t} - \lambda v = \nu \frac{\partial^2 u}{\partial z^2}$$

$$\frac{\partial v}{\partial t} + \lambda u = \nu \frac{\partial^2 v}{\partial z^2} \qquad (1)$$

with boundary conditions:

$$\left(Ru - \frac{\partial u}{\partial z}\right)_{z=0} = k\ (t)$$

$$\left(Rv - \frac{\partial z}{\partial z}\right)_{z=0} = g\ (t)$$

$$u\ (h,\ t) = v\ (h,\ t) = 0 \qquad (2)$$

and initial conditions:

$$u\ (z,\ 0) = U_0\ (z)$$

$$v\ (z,\ 0) = V_0\ (z) \qquad (3)$$

where u (z, t) and v (z, t) are the x- and y-components of the current velocity; λ is the coriolis parameter $\lambda = 2\omega\sin\phi$; ν is the eddy viscosity; R is the surface energy loss coefficient, after Fjeldstad (1930); k(t) and g(t) are related to the x- and y-components of the wind stress by $k(t) = \frac{\tau_x(t)}{\nu\rho}$, $g(t) = \frac{\tau_y(t)}{\nu\rho}$; ρ is the density of water; and h is the depth of the wind-driven current.

The assumptions inherent in this model are that the eddy viscosity is horizontally isotropic, and the currents are horizontal with a negligibly small vertical component.

The decay of the horizontal components of the surface current following a sudden "turn-off" of the wind is shown in Figure 2. The calculations leading

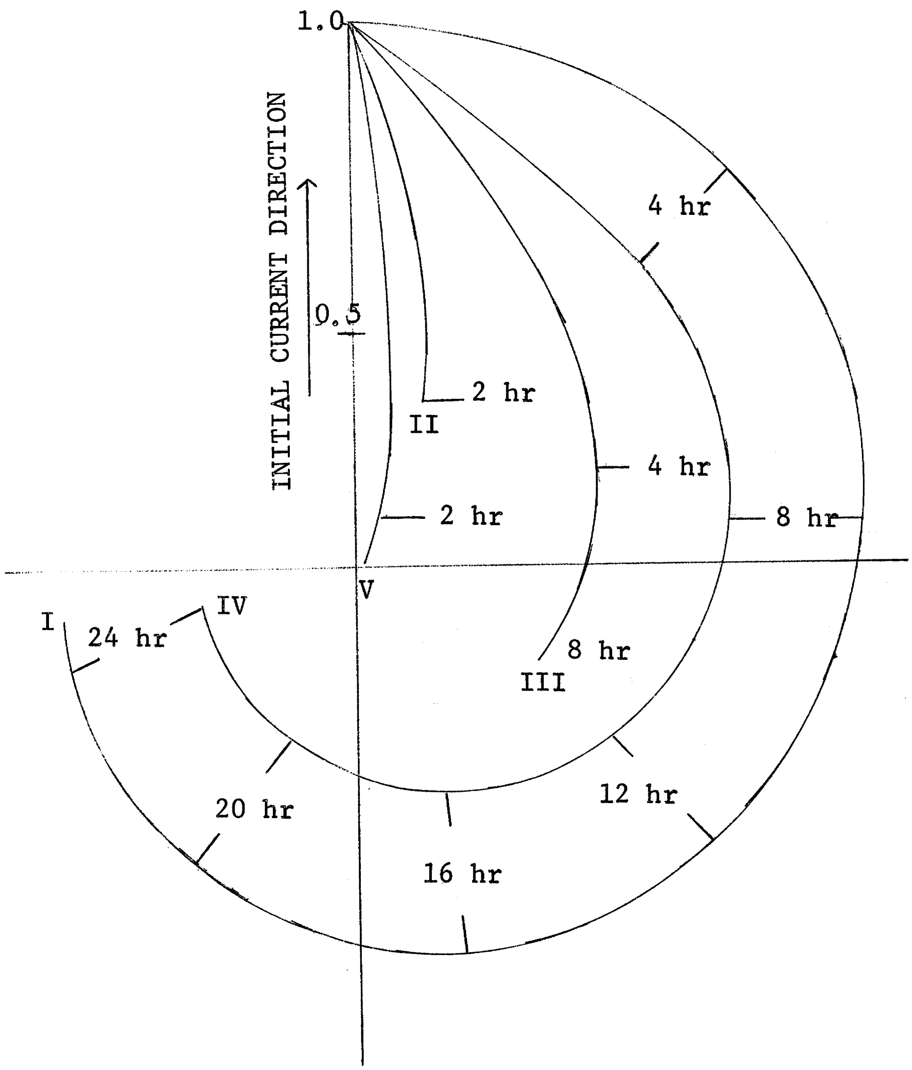


Fig. 2. Hodograph of surface current decay after sudden stoppage of wind.

Current depth 16 m. Lat. 23°N.

Cases I, II, IV, V. Initial current independent of depth.

Case III. Initial current Ekman spiral.

Case I: $\nu = 10\ cm^2/sec$, $R = 0$. Case II: $\nu = 200\ cm^2/sec$, $R = 0$.

Case III: $\nu = 10\ cm^2/sec$, $R = 6 \times 10^{-4} cm^{-1}$.

Case IV: $\nu = 10\ cm^2/sec$, $R = 6 \times 10^{-4} cm^{-1}$.

Case V: $\nu = 200\ cm^2/sec$, $R = 6 \times 10^{-4} cm^{-1}$.

to these results have been described by Noble (1965a). There is an error in the previous paper that was revealed by the continuation of the calculations by analog computer. The error is in the value of the coriolis parameter used in the previous calculations. λ was taken to be $\lambda = \omega \sin\phi$, instead of $\lambda = 2\omega \sin\phi$. The results previously reported pertain to a latitude of 23°N, rather than to 44°N as indicated. There is no essential change in the results except that slightly different values for the eddy viscosity will be necessary to fit the data to the current decay measurements described by Ayers et al. (1958). However, since the numerical values reported by Ayers were obtained by synthesizing the observed currents from hindcasts based on the computed wind fields over the ten days preceding the current determinations, the current decay illustrated in Figure 2 will still provide only a qualitative fit to the data, and no essential improvement in the values of the eddy viscosity and surface energy loss coefficient may be expected.

The qualitative agreement between the early calculations and the field measurements indicated the validity of the circulation model within the limitations of the scale of measurement. For the computations carried out in this investigation, the eddy viscosity appeared to have a value of the order of 10 cm^2/sec, and the surface energy loss coefficient could be of the order of $6 \times 10^{-4}\ cm^{-1}$.

<u>Analog Computation of Transient Current Response to the Wind</u>

The Ekman-type equations (1), with boundary conditions (2), and initial conditions (3) were programmed on the University of Michigan Meteorology and Oceanography Department's hybrid analog-digital computer according to the technique described by Brock (1961). The accuracy of the analog method was verified by machine computation of the current decay problem discussed above. This comparison revealed the arithmetic error also indicated above, but otherwise verified the accuracy of both methods and demonstrated that there is no essential change in the qualitative nature of the solutions for a rather wide variation of empirical parameters.

The current decay problem was not continued because of the lack of precise experimental data for quantitative comparison of results.

The wind and current profile data from USPHS buoy Station 8 in Lake Michigan were scanned to select periods of data for application of the transient response calculations. Instantaneous currents from each meter (10, 15, 22, 30, and 60 meter depths) were used as the initial conditions in the current

equations. The surface wind data from the station anemometer were smoothed and used for the wind stress input. The calculated currents were plotted out and compared with the actual station records to determine the suitability of the theoretical model. The eddy viscosity and drag coefficients were manipulated over a wide range in an effort to force a fit between the computed currents and the station records.

A major computational problem arose in that the initial conditions could not be specified at the water surface because the first current meter was at a depth of 10 m. The use of an analog computer, however, made it a simple matter to change the initial specification of the surface current and to determine the effect on the computed results. The current profile beginning at 10 m (as given from the station data) was extrapolated to the surface for the initial conditions. This extrapolation was attempted linearly, with increasing speed toward the surface, with decreasing speed toward the surface, and both with and without (Ekman) rotation from the experimental profile. (As used herein, the term profile refers to the 3-dimensional curve defined by the locus of the tips of the 2-dimensional current vectors at each of the levels of measurement.)

The wind stresses were taken as both linear and quadratic functions of the wind speed. The drag coefficient was varied over a wide range to attempt to force a fit between the observations and the computations.

The temperature records from Station 8 have indicated that the thermocline was at approximately 25 m during the late-summer period for which the current records have been examined. Therefore, several forms for the vertical variation of the eddy viscosity have been considered to account for the effect of the existence of the thermocline upon the vertical current structure.

A 14-hour period of data from 26 September 1963 has been selected for detailed discussion of the failure of the Ekman-type model in the prediction of transient wind-driven currents. Figure 3 is a hodograph of the surface air velocity vector for this period (beginning at 0400 EST). The hodograph is smoothed by plotting the locus of the 2-hr average values of the air velocity. The air motion was initially to the south of east, increased slightly in speed, and turned counterclockwise, ending in a northwesterly direction after 10 hr. During the next 4 hr, the air speed increased and the motion turned clockwise to north.

The hodographs of the currents vectors at the same station during the same period are shown in Figure 4. The initial currents are to the northeast.

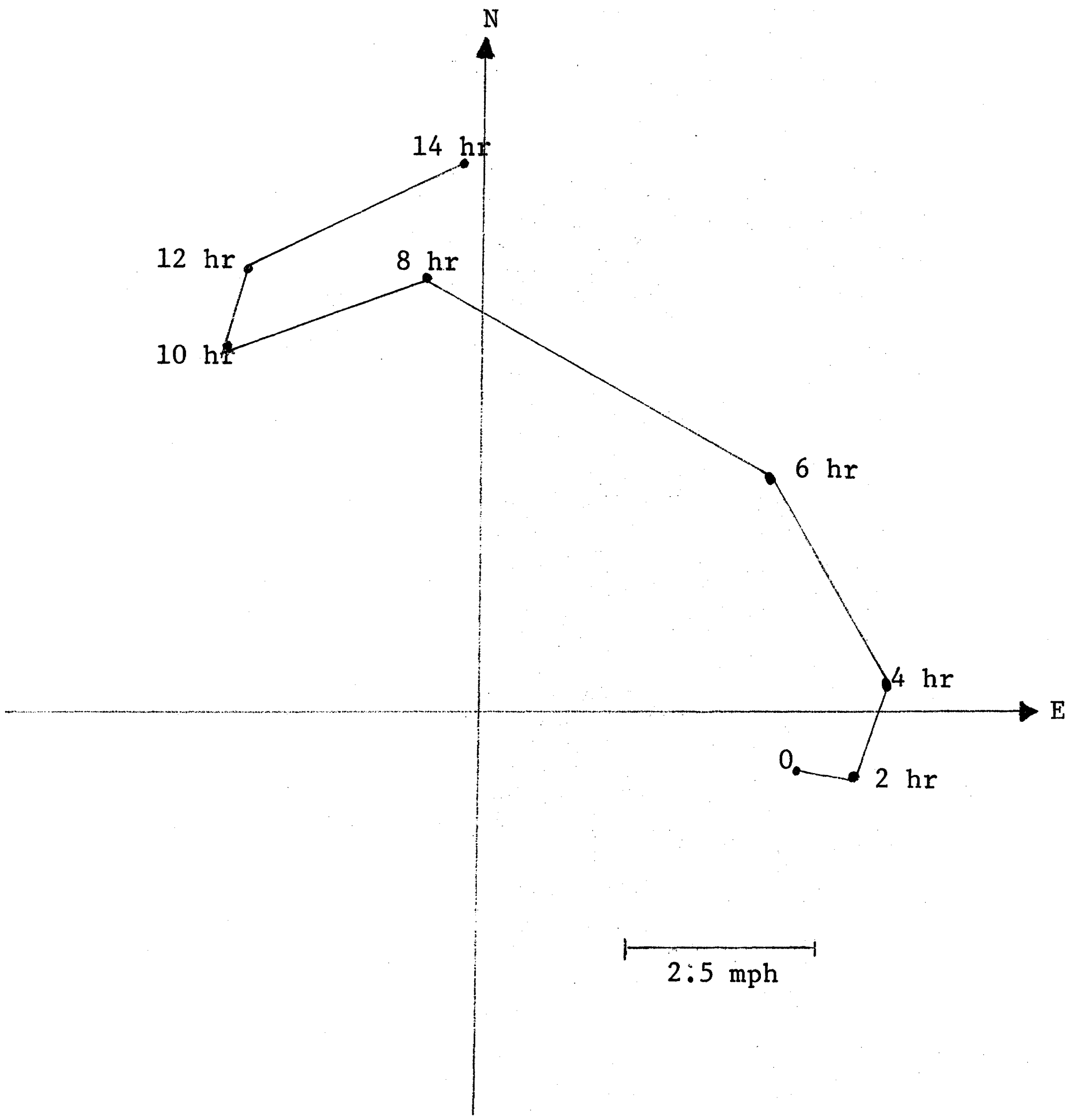


Fig. 3. Hodograph of surface air velocity vector, Station 8, 26 September 1963. 14 hr of record beginning at 0400 EST. Points indicate 2-hr average air velocity.

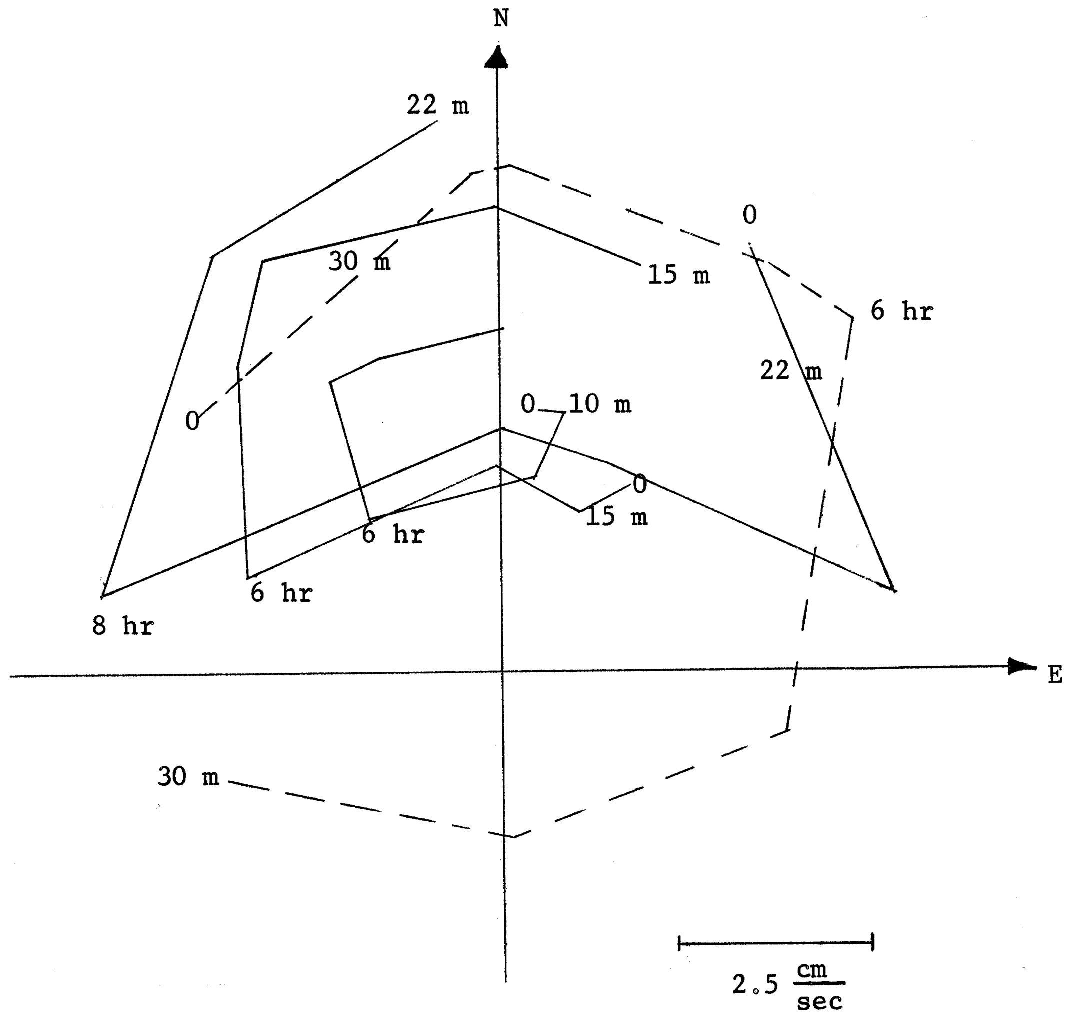


Fig. 4. Hodographs of current vectors, Station 8, 26 September 1963. 14 hr of record beginning at 0400 EST. Points indicate 2-hr average current velocity. 10, 15, 22, 30 meter currents indicated.

The current vectors at 10, 15, and 22 m rotated in a counterclockwise direction for approximately 6 hr, and then turned clockwise for the remainder of the period. The current vector at 30 m was initially northwest, and rotated continuously clockwise (through south) by about 300° in the 14-hr period. Temperature data from this station and from GLRD BT records show that the thermocline was at approximately 25 m during this period. The current vectors above 22 m and at 30 m show different characteristics that appear to indicate the existence of a well-developed thermocline between 22 and 30 m.

In spite of the similarities of the current hodographs at 10, 15, and 22 m with the air velocity hodograph, there are important differences that seem to indicate that the currents are not directly driven by the wind. The current vectors begin a clockwise rotation ater 6 to 8 hr, while the air vector continues its counterclockwise rotation for 10 hr. The water current vectors are generally oriented to the left of the air velocity for the first eight hours. The current speed generally increases with depth.

Selected analog computer solutions for equations (1), with boundary and initial conditions (2) and (3) are shown in Figures 5-8. The solutions apply for the period of data shown in Figures 3 and 4. The initial conditions were taken from the current velocities shown in Figure 4, and the wind stress was derived from the air velocity vector shown in Figure 3. For these solutions, R, the surface energy loss coefficient, was taken to be zero, and the empirical coefficients that could be varied to fit the solutions to the data were the drag coefficient, C_d, and the eddy viscosity, ν. The expressions for the wind stress and the values of the eddy viscosity used to obtain each solution are given in the figures.

It was not possible, using reasonable values for the empirical parameters, to generate an analog solution which resembled the transient response characteristics of the measured currents.

It appears that a fundamental change in the basic concept underlying the theoretical models describing water circulation is necessary.

REEXAMINATION OF EXISTING INFORMATION

The disparity between the results of the analog computations and the transient characteristics of the measured currents led to a consideration of any neglected factors in the conceptual models, and of the meaning of the current meter records from the buoy station.

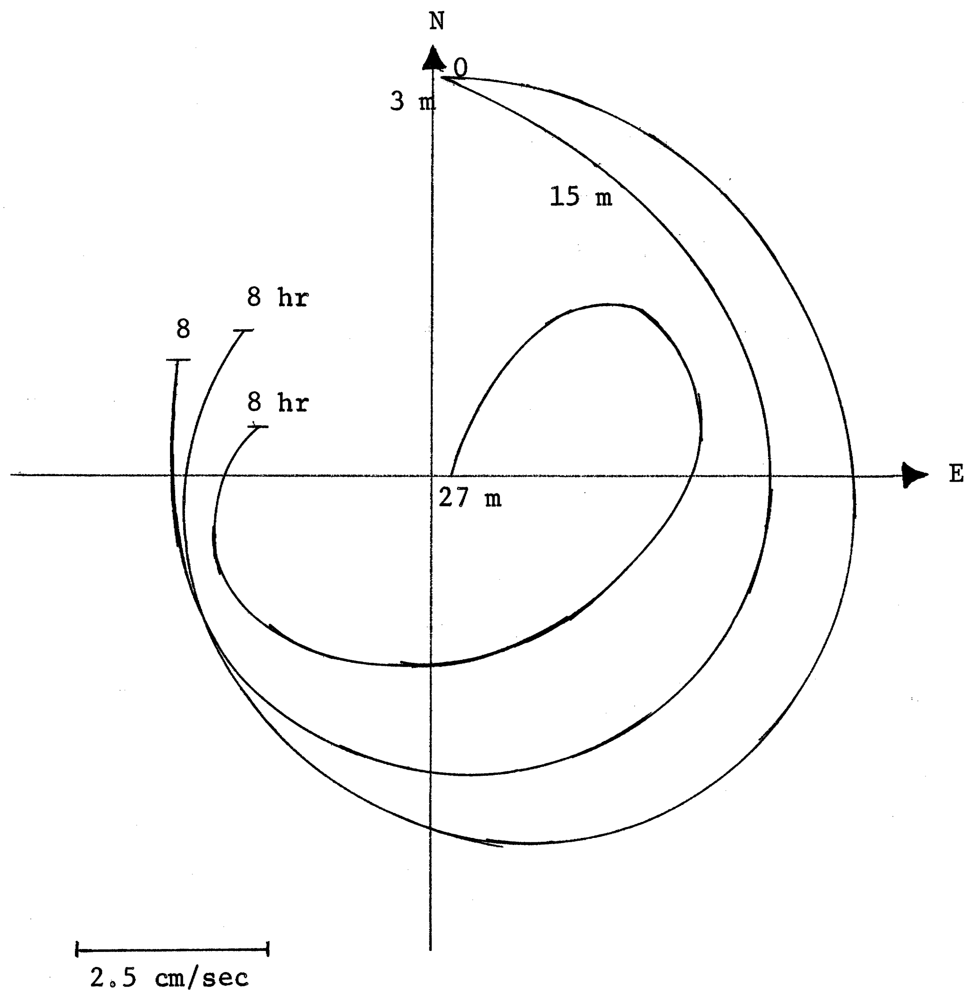


Fig. 5. Hodograph of analog computer solution for wind-driven currents predicted by Ekman-type model for data period shown in Figures 3 and 4.

$h = 60$ m

$\nu = 100$ cm^2/sec,

$(0 \leq Z \leq 60$ m);

$\tau = 3 \times 10^{-6} W^2$

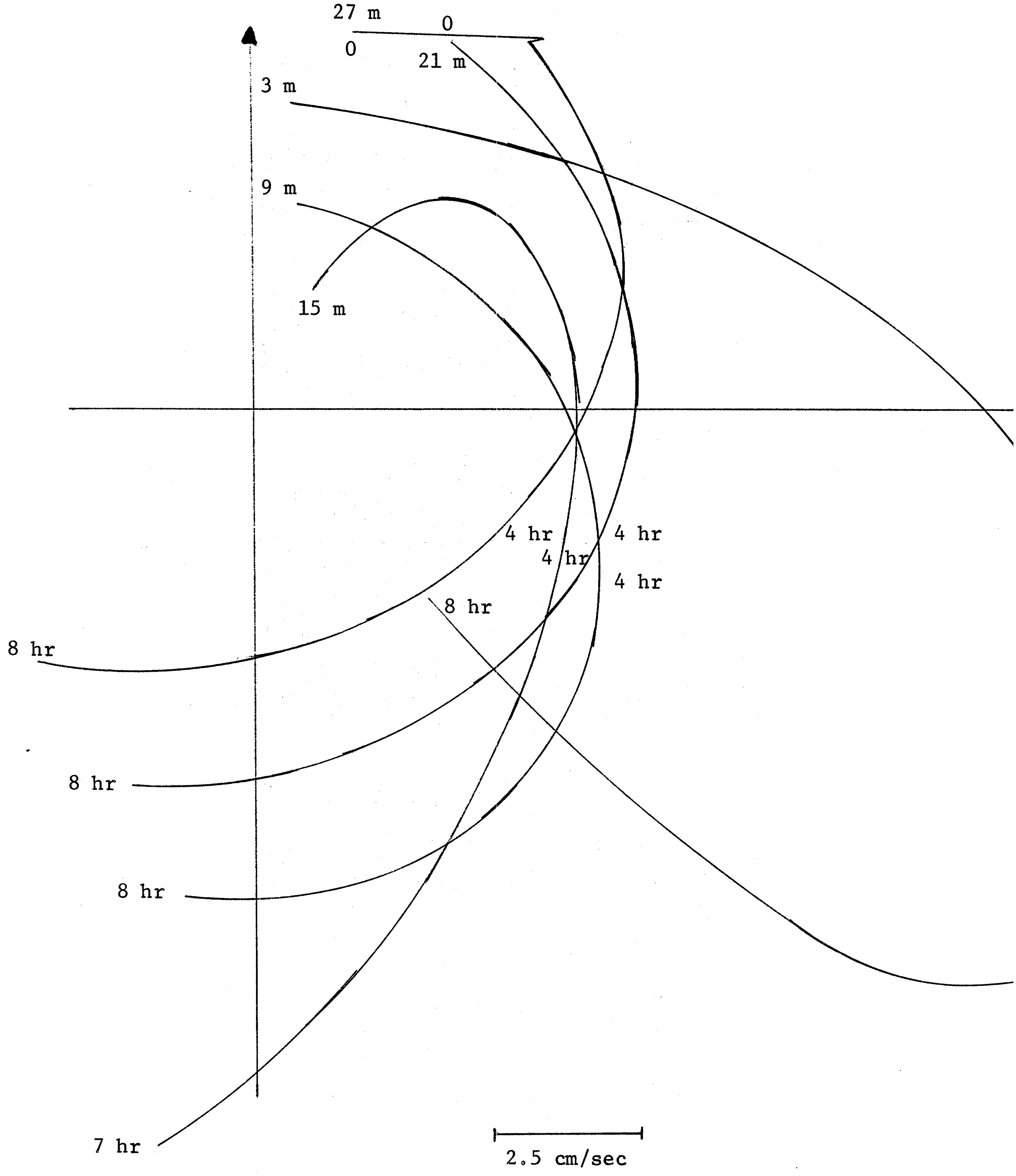


Fig. 6. Hodograph of analog computer solution for wind-driven currents predicted by Ekman-type model for data period shown in Figures 3 and 4. h = 60 m $\nu = 10\ cm^2/sec$, $(0 \leq Z \leq 25\ m)$; $\nu = 100\ cm^2/sec$, $(25 < Z \leq 60\ m)$; $\tau = 3 \times 10^{-5} W^2$

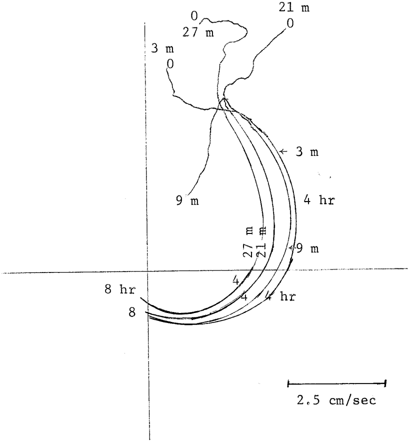


Fig. 7. Hodograph of analog computer solution for wind-driven currents predicted by Ekman-type model for data period shown in Figures 3 and 4.

$h = 60$ m

$\nu = 1000$ cm^2/sec,

$(0 \leq Z \leq 60$ m$)$;

$\tau = 3 \times 10^{-6} W^2$

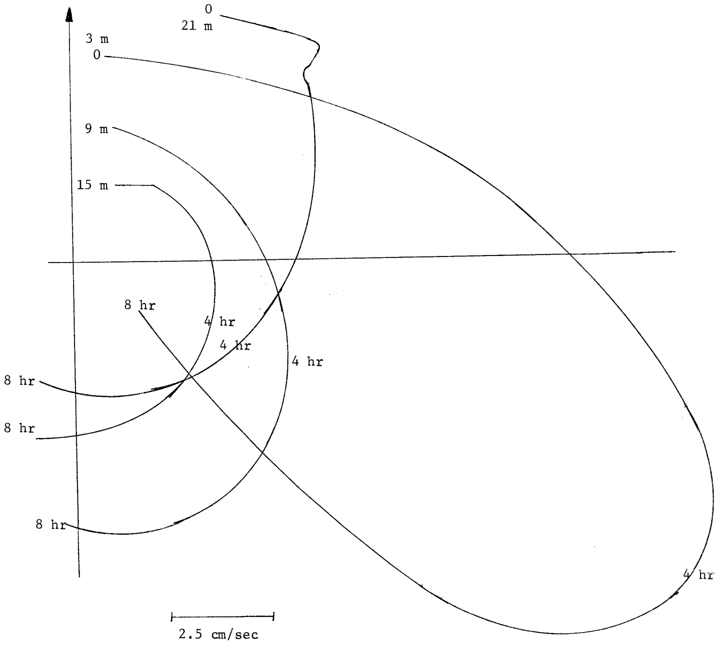


Fig. 8. Hodograph of analog computer solution for wind-driven currents predicted by Ekman-type model for data period shown in Figures 3 and 4.

$h = 60$ m

$\nu = 10\ \mathrm{cm}^2/\mathrm{sec}$,

$(0 \leq Z \leq 25$ m);

$\nu = 0$,

$(25 < Z \leq 60$ m);

$\tau = 3 \times 10^{-5} W^2$

Super (1962) has conducted some experiments on the measurement of the relationship between wind and current in the upper layer of Lake Mendota. The results of his measurements yield a value of 0.5 cm^2/sec for the eddy viscosity, and indicate the dpeth of the Ekman spiral to be of the order of 5 m. Carrier and Robinson (1962) have used a value of 10^8 cm^2/sec for the value of the eddy viscosity in their calculation of the Gulf Stream dynamics. It therefore appears that the eddy structure which is the mechanism for energy distribution and dissipation in the fluid system may well be related to the size of the fluid system.

The dominant characteristic of the records from the current meters at the buoy stations in Lake Michigan is the persistent rotation of the current vector at the station. Verber (1964) presents examples of these rotations in his discussions of measurements at Station 1 in the south end of Lake Michigan.

Since the rotational features are dominant in the current records, and since the currents do not show a direct transient response to the surface wind, and since the eddy viscosity appears to be related in some way to the basin size, a geostrophic eddy structure seemed to suggest itself as the basic current mechanism. The desirability of considering a geostrophic eddy structure in the description of water currents is enhanced when proper attention is given to the implications of the Eulerian to Lagrangian transformation inherent in the interpretation of current meter records. When the hourly wind vectors from a weather station are added cumulatively (as is usually done with current meter data), the shape of the displacement curve is remarkably similar to those obtained from current data. Figure 9 is a plot of the cumulative wind vector as observed at Grand Rapids, Michigan, from November 1963. The wind record is the direct result of measurement of a passage of a series of contra-rotating geostrophic eddies (high and low pressure cells).

Studies of the current structure in southern Lake Michigan by Ayers (1963) and Ayers and Bellaire (1964) with drogues and with dynamic height computations have revealed "streaks" of oppositely directed current, and suggestions of eddies of different sizes and of both right-hand and left-hand rotation probably moving within an overall drift. These calculations were reported for the upper layers of the lake and showed some correlation with the surface temperature structure. These results were supported by the results of earlier drift bottle studies reported by Johnson (1960) and Van Oosten (1963). These patterns seem to be persistent in the lake.

The current meter data were reexamined to see if a geostrophic eddy

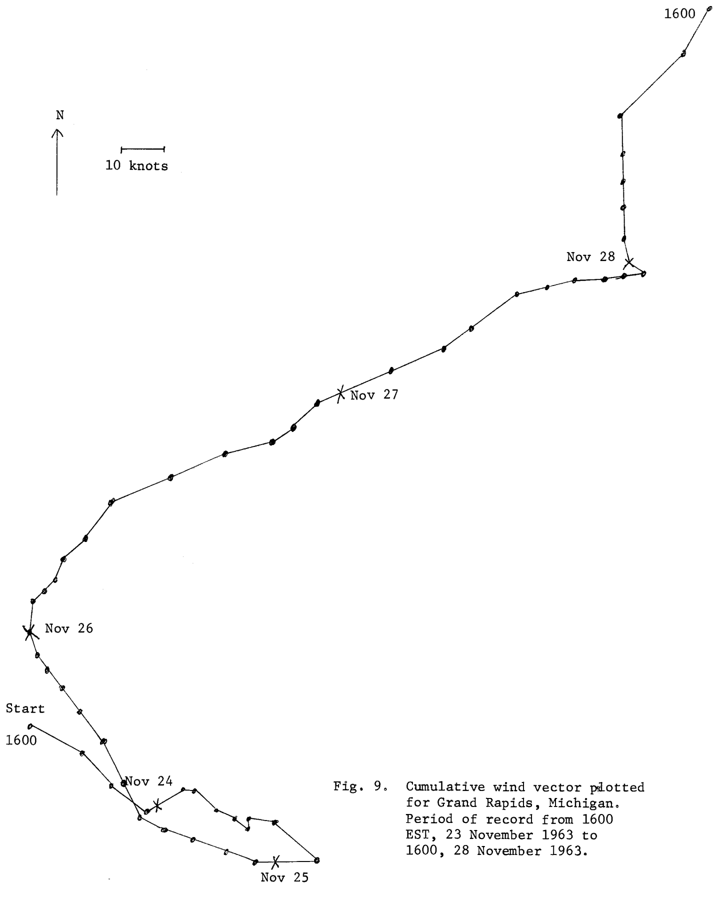


Fig. 9. Cumulative wind vector plotted for Grand Rapids, Michigan. Period of record from 1600 EST, 23 November 1963 to 1600, 28 November 1963.

structure might give results comparable to the field observations. A simplified contra-rotating eddy structure which is uniformly distributed over the lake surface was assumed as shown in Figure 10. It was further assumed that the eddies moved past the current station with a drift velocity that is small as compared with the rotational velocity about the center of the eddies. It is further assumed that the eddies are of a uniform size and have a uniform rotational speed. Figure 10a is a schematic representation of the eddies distributed in a square array. If the field of eddies were passing the current meter with a slow drift velocity in a northerly direction, the current meter readings would be the same as though the meter were moving through the eddy field in a southerly direction. Figure 10b is a schematic representation of the instantaneous current vectors that would be recorded by a current meter moving through two eddies with a velocity $\vec{V}$. The path of motion was arbitrarily taken from A to B as shown in Figure 10b. The current vector would make one complete rotation as the current meter traversed through two eddy diameters. The rate of rotation of the current vector would be determined by the ratio of the translational velocity to the eddy diameter. The instantaneous current speed would be determined by a vector addition of the translational velocity with the eddy rotational velocity.

Several periods of current meter data were examined in terms of the postulated eddy structure to see if a reasonable circulation pattern might evolve. One of the selected periods of current meter data is shown in Figure 11. The translational and rotational components of the currents were separated from the current speed data as follows:

Assuming the drift velocity to be less than the rotational velocity, and that the instantaneous current vector is give by

$$\vec{V}(t) = \vec{V}_{\omega}(t) + \vec{V}_{T}(t)$$

where $\vec{V}_{\omega}(t)$ is the rotational velocity, and $\vec{V}_{T}(t)$ is the translational velocity, then the maximum value of the current speed is

$$V_{max} = V_{\omega} + V_{T}$$

and the minimum value of the current speed is

$$V_{min} = V_{\omega} - V_{T}$$

(provided that the current meter does not pass through the center of the geostrophic eddies). Further, since it is postulated that one complete rotation of the current vector occurs when the current meter passes through two eddy

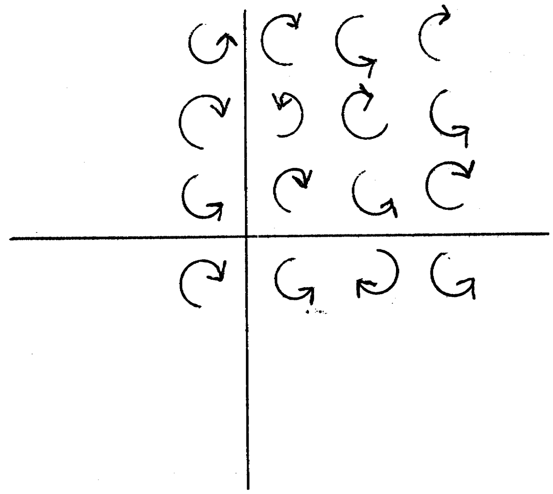


Fig. 10a. Uniform distribution of contra-rotating eddies.

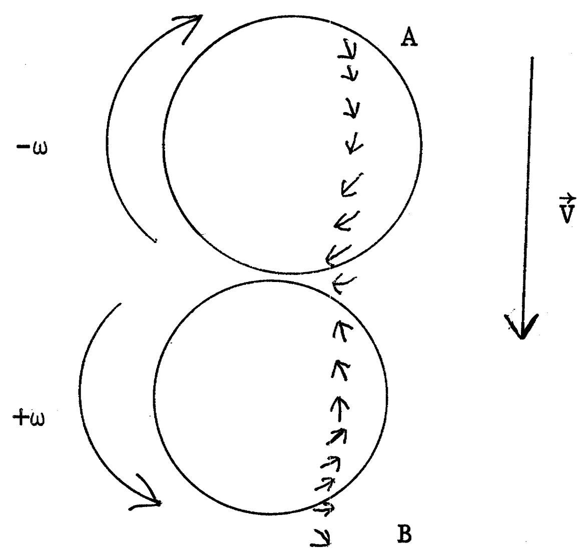
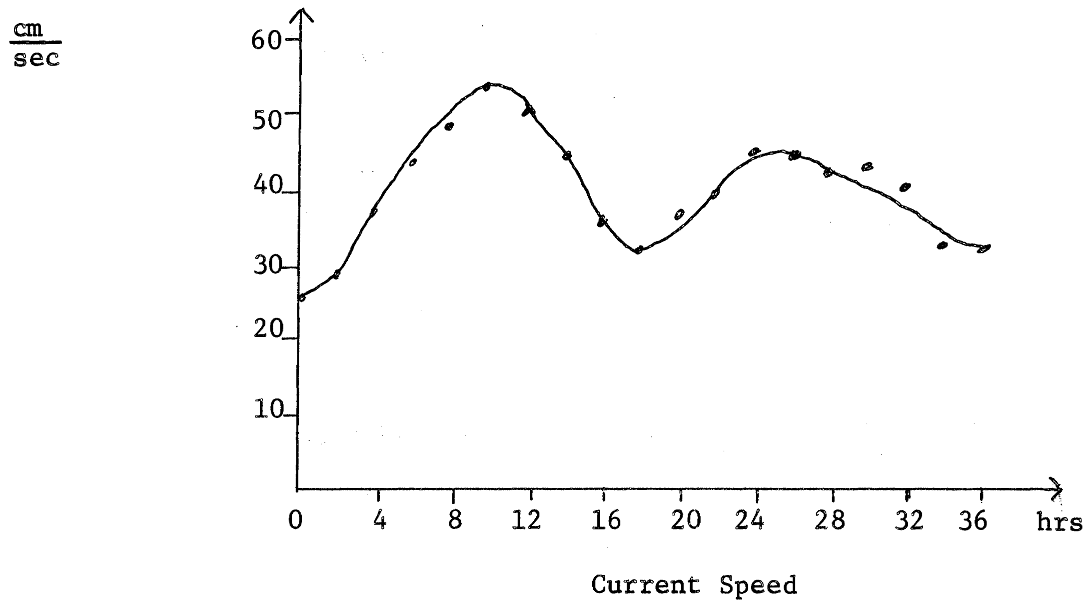


Fig. 10b. Current vectors recorded by current meter moving from A to B through two contra-rotating eddies.



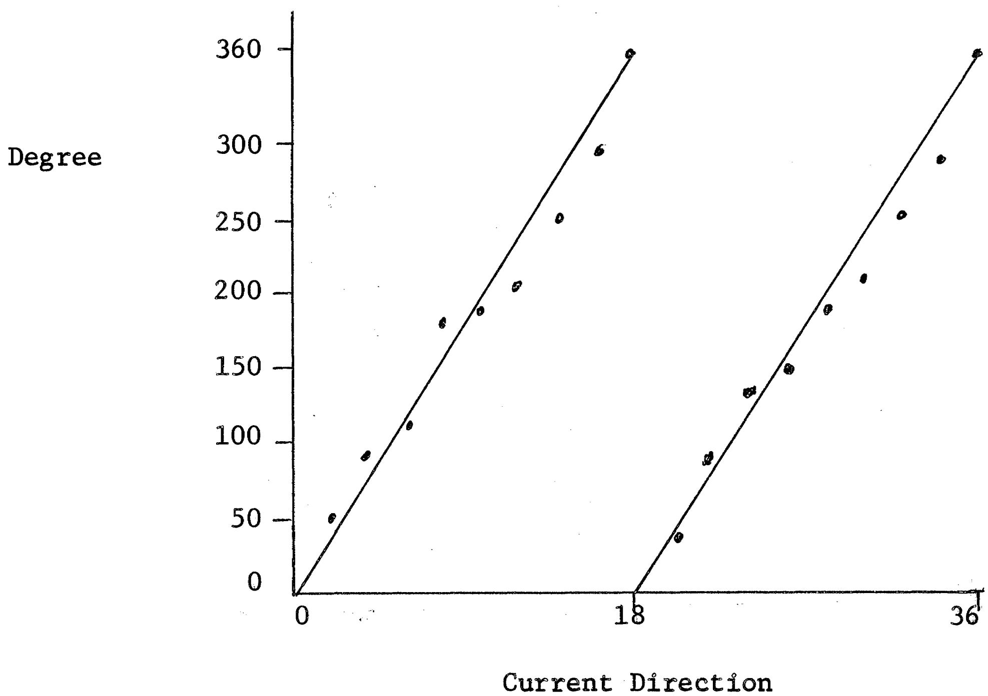


Fig. 11. Current speed and direction. Station 8, 10-meter depth, 0000 EST 7 August 1963 to 1200 EST 8 August 1963.

diameters, the size of the eddy is related to the period of rotation of the current vector and the translational velocity of the eddies.

$$d = \frac{\tau V_T}{2}$$

where d is the eddy diameter, and τ is the period of rotation of the current meter.

For the period of data shown in Figure 11, the values for the eddy diameter, rotational speed, and translational speed are:

$$d = 3.8 \text{ km}$$
$$V_\omega = 42 \text{ cm/sec}$$
$$V_T = 12 \text{ cm/sec}$$

These values are representative of those obtained for each of several periods of data.

EXPERIMENTAL VERIFICATION OF THE GEOSTROPHIC EDDY MODEL

The geostrophic eddy model was conceived as an exercise in heuristic logic. The Ekman model did not work. It was necessary to provide an alternate explanation for the current meter observations. The geostrophic eddy structure could provide a means for obtaining the type of current meter records that were observed in field experiments. Further, the geostrophic eddy model was suggested by experimental verification in the global-scale fluid system called the atmosphere. Therefore, before the geostrophic eddy model could be logically applied to bodies of water, the existence of contra-rotating eddies had to be documented by experimental measurements.

The values for the eddy diameter, rotational speed, and translational speed obtained from analysis of the experimental data indicated that the usual time scale of observation of the motion of current drogues would mask the existence of such eddies. It was therefore decided to conduct some field experiments in cooperation with a Coherent Area program (WP 00311) at the Great Lakes Research Division, University of Michigan. Typically, in Great Lakes research, the positions of current drogues are fixed at intervals of several hours duration. The time averaging inherent in the drogue measurements would tend to mask the existence of the geostrophic eddies. It was therefore decided to conduct some experiments in which the current drogues were fixed at 20-minute intervals so that the eddies could be determined.

Two experiments were carried out in the late summer of 1965. The first

experiment is shown in Figure 12 and the second in Figure 13. Both experiments were conducted about 10 miles offshore in approximately 95 meters water depth. For the first experiment, the drogues were set in a straight line with 1/2 mile separation between drogues. Figure 11 shows that drogues 3, 6, 7, and 8 moved in a clockwise direction, 1 and 5 moved in a counterclockwise direction, and the motions of 2 and 4 were interpreted as being primarily translational. This experiment demonstrated the existence of contra-rotating eddies of about 3 km diameter, with a rotational speed of 75 cm/sec.

For the second experiment, the drogues were set in a right-angle array with logarithmic spacing between drogues, as shown in Figure 13. The results of the second experiment were interpreted as a pair of contra-rotating eddies moving in an easterly direction with a translational speed of 7.5 cm/sec. During the second experiment, drogues 1 through 3 indicated a clockwise eddy, and drogues 6 through 8 indicated a counterclockwise eddy.

During both of these experiments, the drogues were set at the "surface," i.e. they measured the currents in the upper 6 ft of the water.

In an independent experiment conducted by Dr. J. C. Ayers (personal communication), drogues were set at several depths at a single point. The observations from this third experiment have been provided by Ayers, and are shown in Figure 14. The results of Ayers' experiment are interpreted as showing that the eddy structure is deep, with perhaps decreasing rotational speed with increasing water depth.

Ayers' (1963-4) BT transects across Lake Michigan were duplicated to further substantiate the eddy structure. The results from the transect from Racine to Grand Haven on 9 November 1962 are shown in Figure 15. The surface temperature profile has been obtained from the surface readings of the BT casts. The north-south current components were calculated from the BT soundings by the dynamic height method. For the purposes of this project BT casts were made from two ships running parallel courses across Lake Michigan from Holland to Racine. The INLAND SEAS* sailed across the lake 2 miles north of the MYSIS*, and was two miles south on the return trip. BT casts were made at 2-mile intervals along the cruise track of each ship. The resulting BT casts were thus at the corners of a 2-mile square array in a line transecting the southern basin of Lake Michigan. The BT data were used to compute dynamic height anomalies, and to obtain dynamic height currents between the various

*Research vessel of the Great Lakes Research Division, University of Michigan.

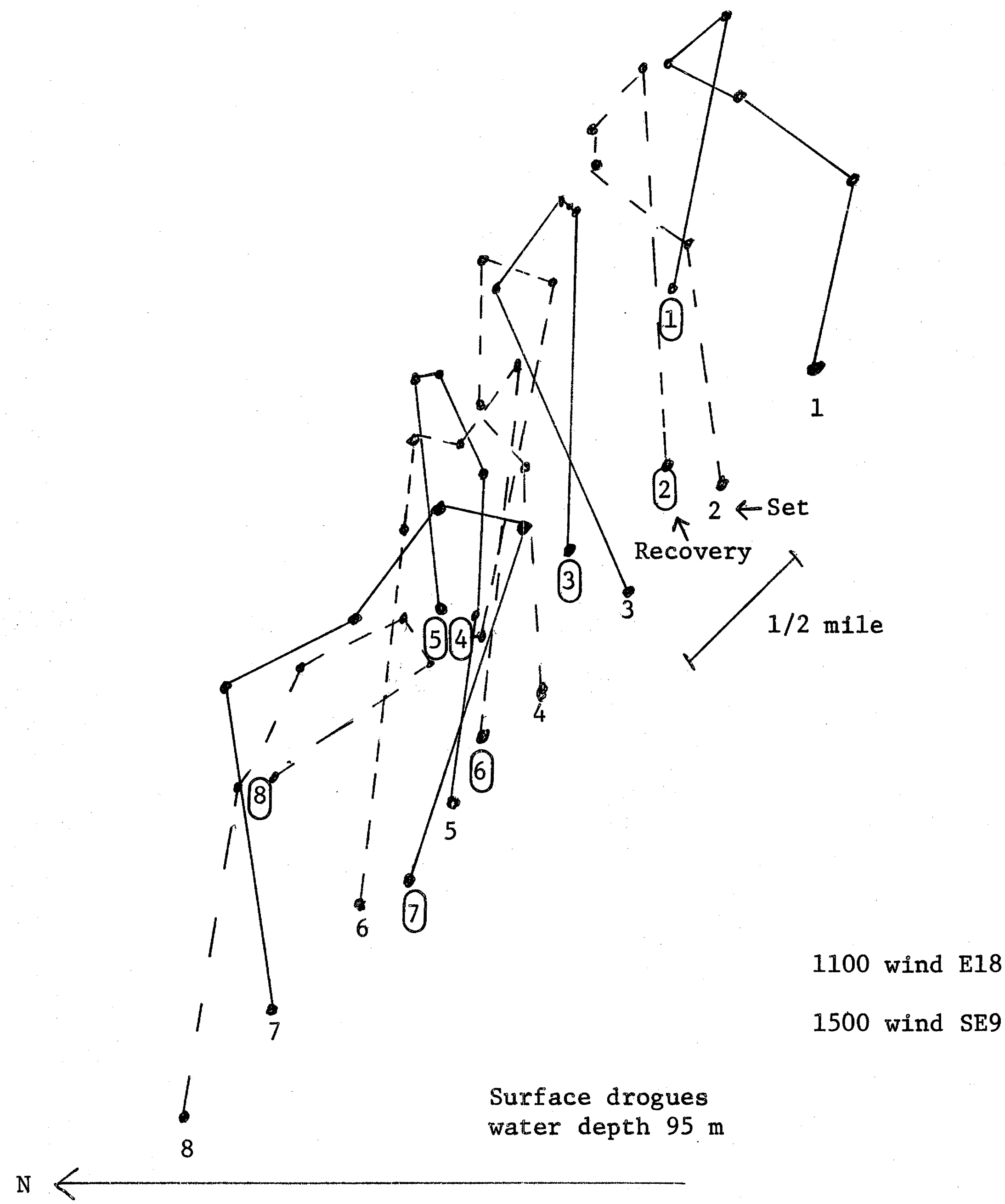


Fig. 12. Drogues set in straight line, 1/2 mile spacing, 27 September 1965. Set at 1023, recovered at 1643 EST. Positions fixed at approximately 30-min intervals. Note convergence of recovery positions (circled).

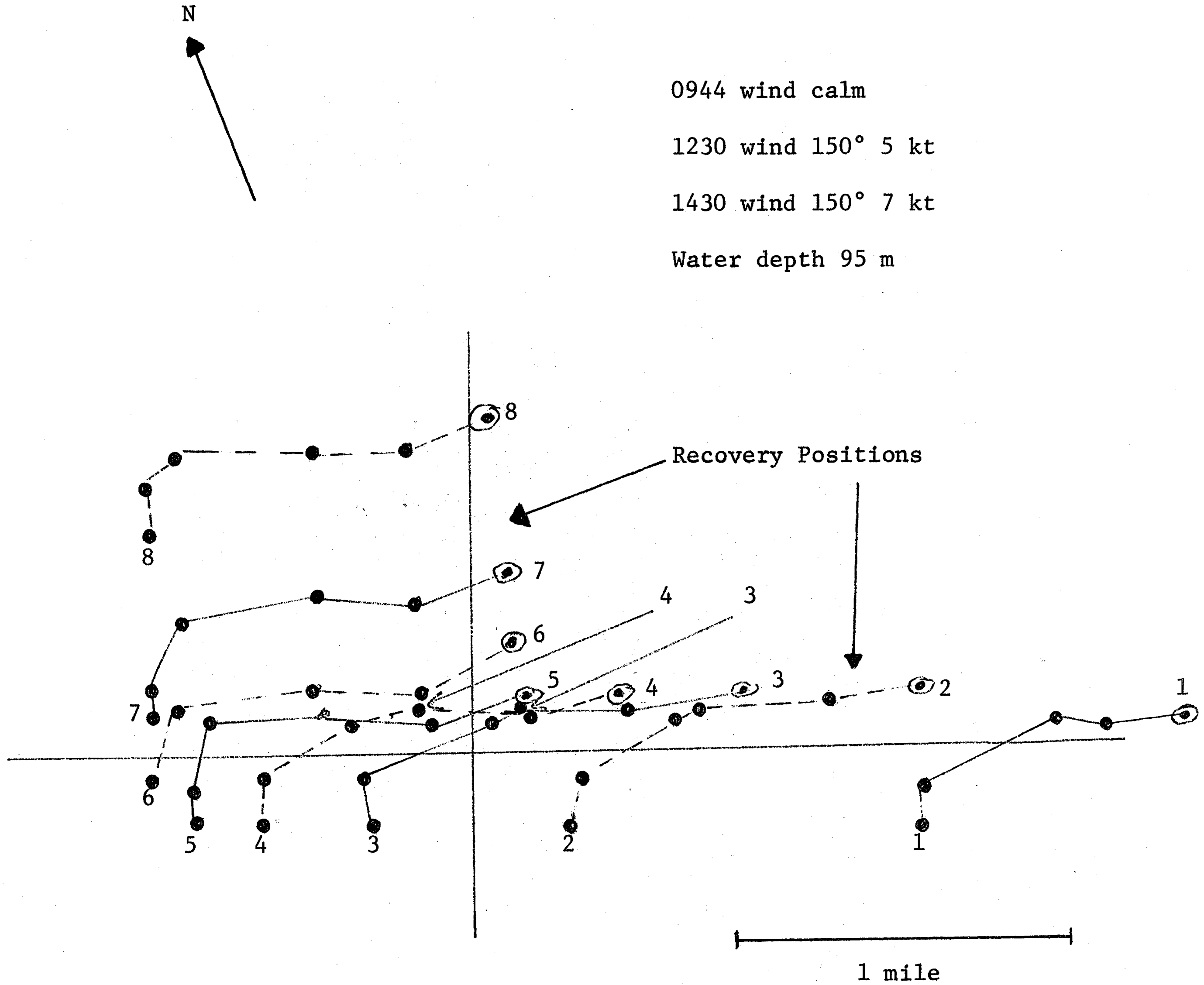


Fig. 13. Surface drogues set in right-angle array variable spacing. Set at 0944, recovered at 1515 EST, 29 September 1965. Positions fixed at approximately 20-min intervals.

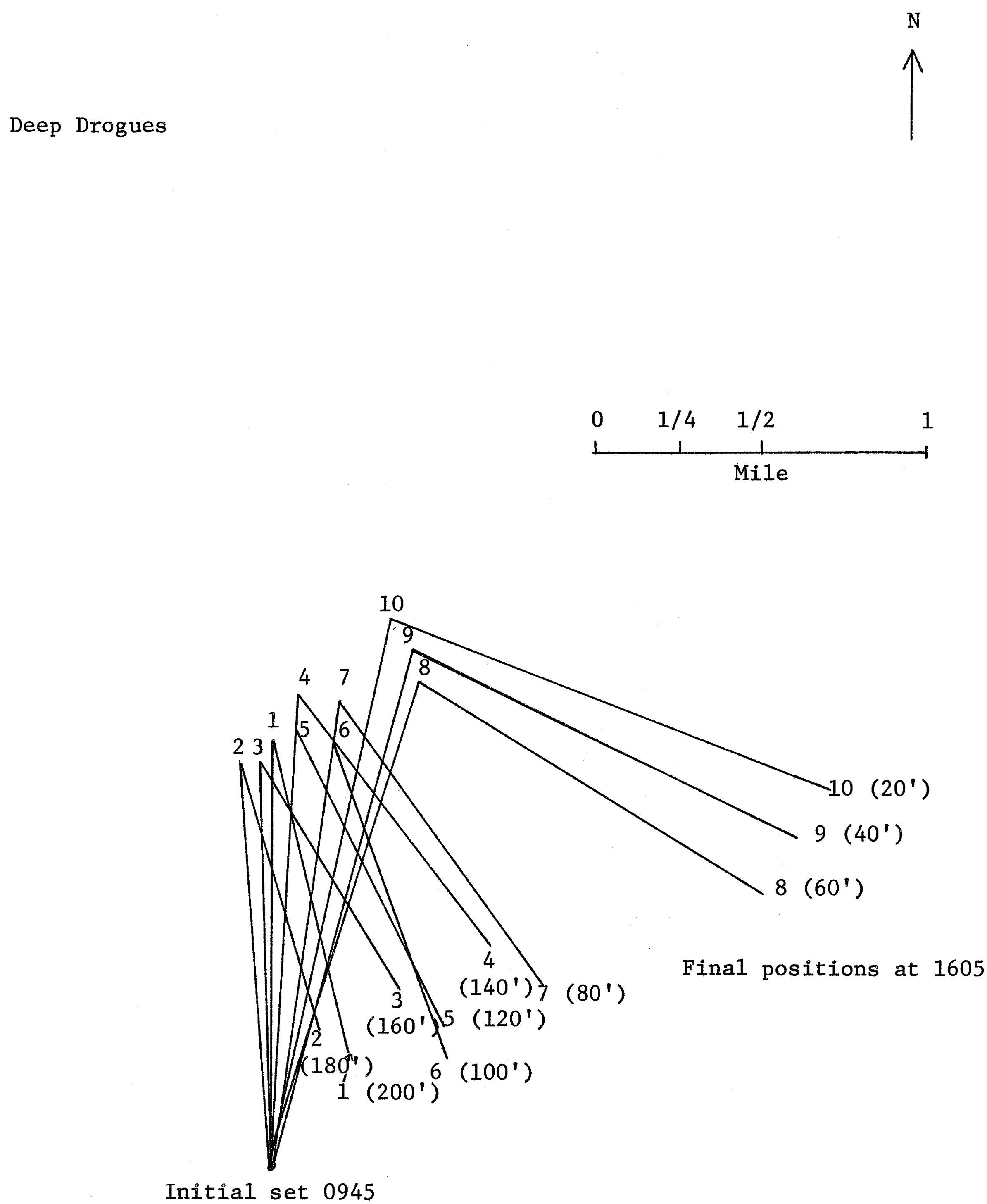


Fig. 14. Deep drogue experiment conducted by J. C. Ayers, 11 November 1965.

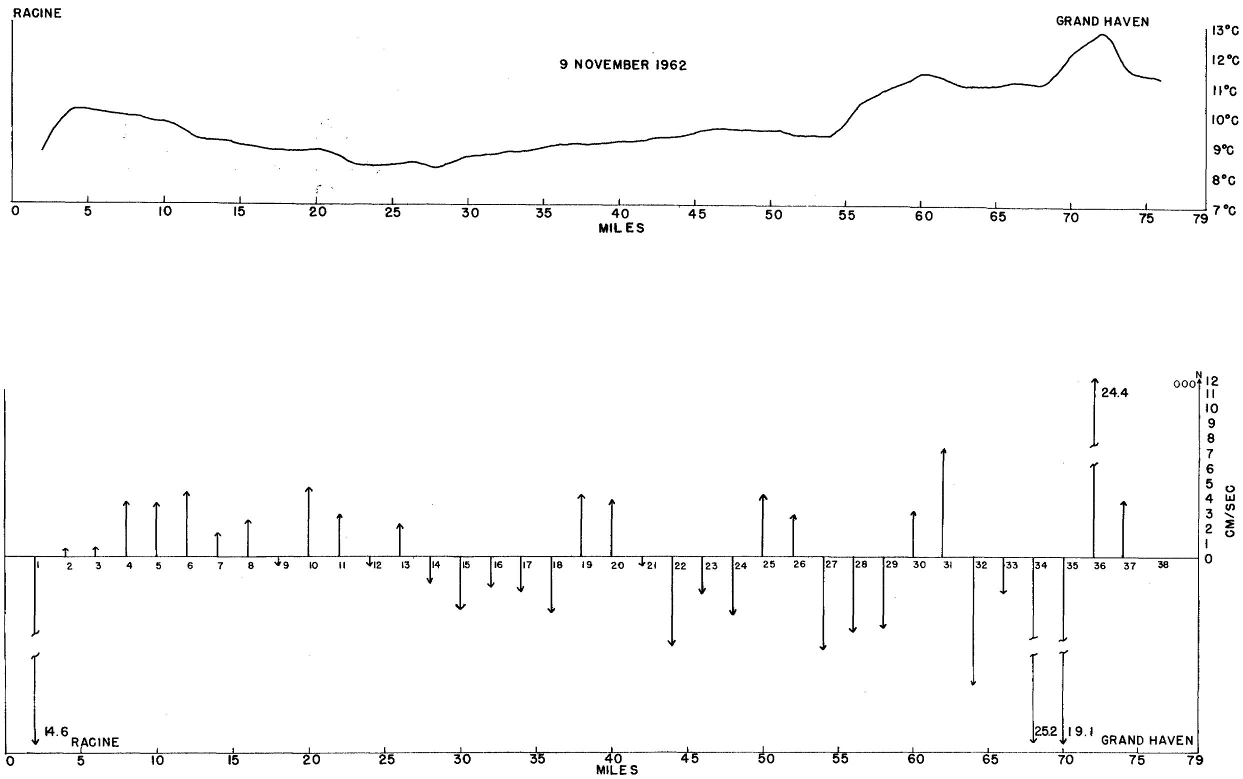


Fig. 15. Top: Surface temperature transect. Bottom: Velocity vectors computed by dynamic heights. November 9, 1962. Data from Ayers 1963.

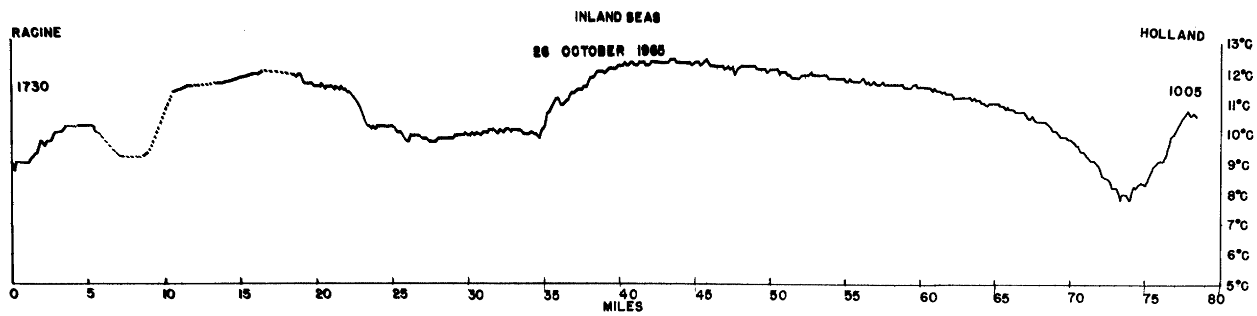
pairs of casts in a line across the lake. The BT transect from Holland to Racine on 26 October 1965 had to be aborted midway across the lake because of weather. A NW gale moved in, and the return crossing could not be made until 1 November 1965. Surface temperatures were continuously recorded on both crossings of the lake. In Figures 16 and 17, the dynamic height currents calculated from the BT transects are compared with the surface temperature patterns. There appears to be a correlation between the surface temperature structure and the dynamic height currents. In Figure 18, the north-south current components calculated along the lines are added to the east-west components between the lines for the 1 November transect. Counter-rotated eddy structures may be inferred from these data.

Prototype instrumentation was developed for the measurement of surface water temperatures during the drogue experiments on 27 September 1965 and 29 September 1965. The new instrumentation was based on a thermistor towed in the surface water from a bow-sprit on the INLAND SEAS. Due to instrumental problem with the prototype, it was not possible to exactly compare the water surface temperature structure with the drogue observations. However, in the general area in which the drogue measurements were carried out, the surface temperature pattern showed sinusoidal fluctuations with an amplitude of 0.02C and with a wave-length of approximately 2.4 km. It was presumed that this surface temperature structure was related to the geostrophic eddy structure indicated by the drogue measurements.

THE POSSIBLE ORIGINATION OF GEOSTROPHIC EDDIES IN THE LAKE

Temperature records reported by Noble (1965b), and surface temperature patterns described by Rodgers (1965) and Ragotzkie and Bratnick (1965) show conclusively that the lake warms from the edge to the center. Further, Rodgers reports alongshore currents of the order of 15 cm/sec in the zone of maximum horizontal temperature gradient. Using a simplified approximation to the temperature structure data presented by Rodgers, and applying the method of dynamic heights to calculate the current, the computed alongshore geostrophic current due to the density gradient created by the temperature structure has a speed of 9 cm/sec. The direction of the computed current agrees with the experimental observations by Rodgers.

It therefore may be postulated that the spring warming of the water in the lake gives rise to a geostrophic eddy structure that is of the same size



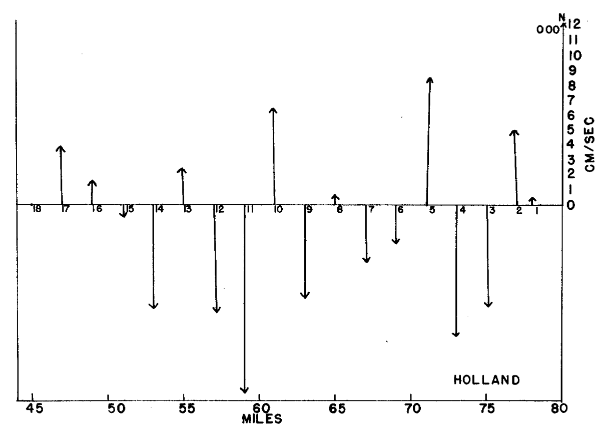


Fig. 16. Top: Surface temperature transect. Bottom: Current vectors computed by dynamic heights. INLAND SEAS, October 26, 1965.

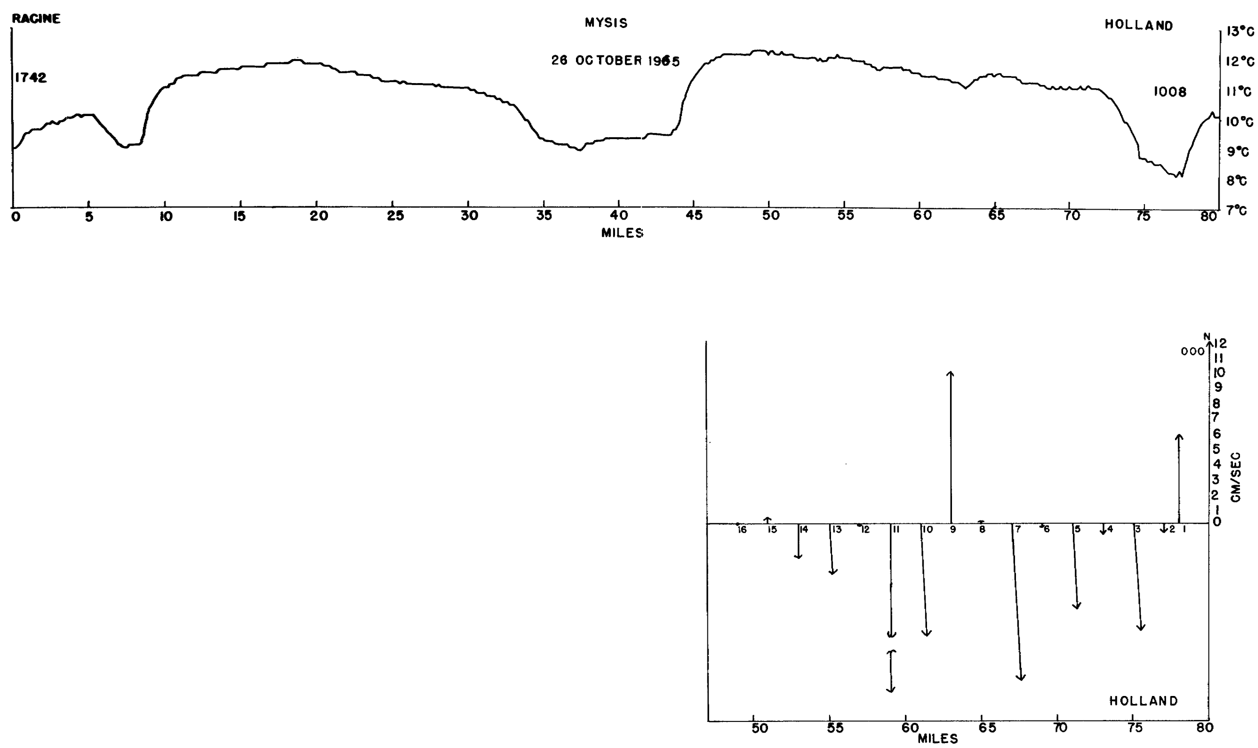


Fig. 17. Top: Surface temperature transect. Bottom: Current vectors computed by dynamic heights. MYSIS, October 26, 1965.

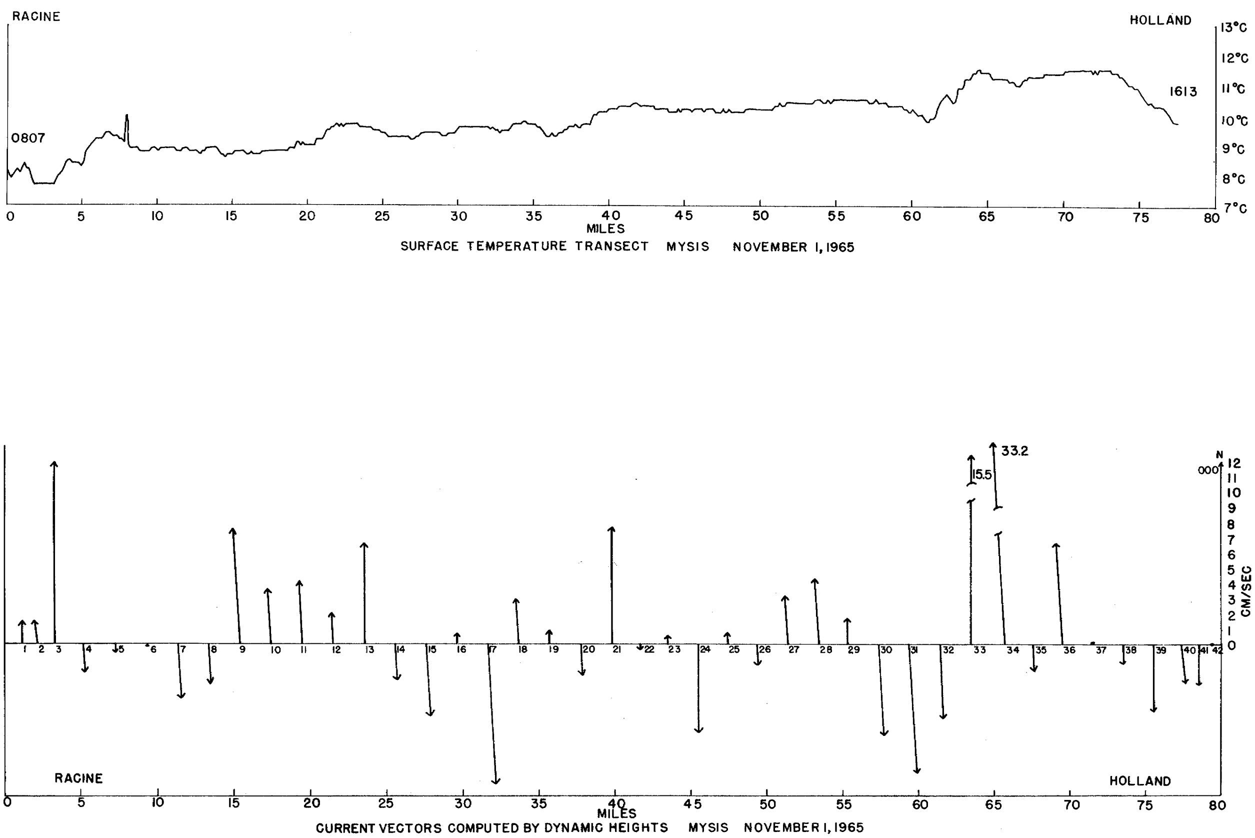
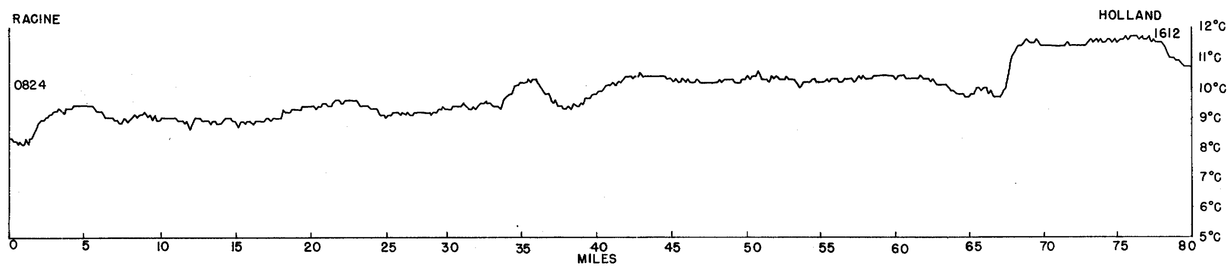
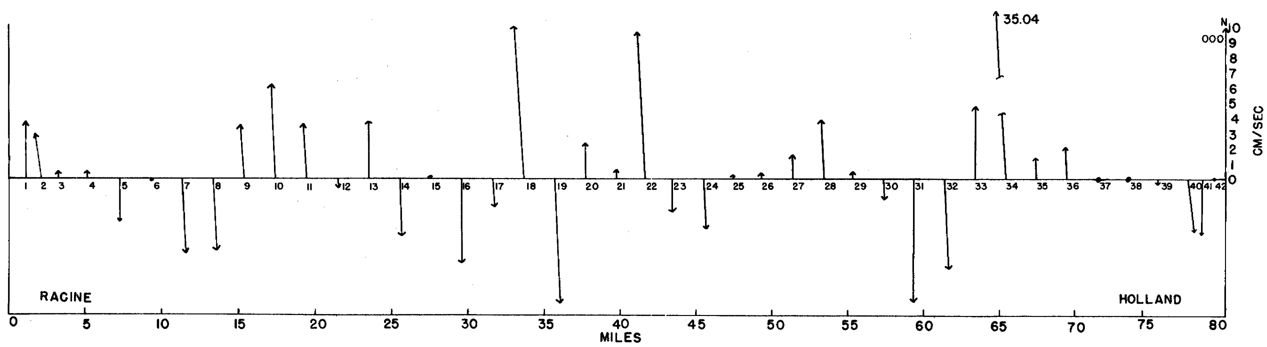


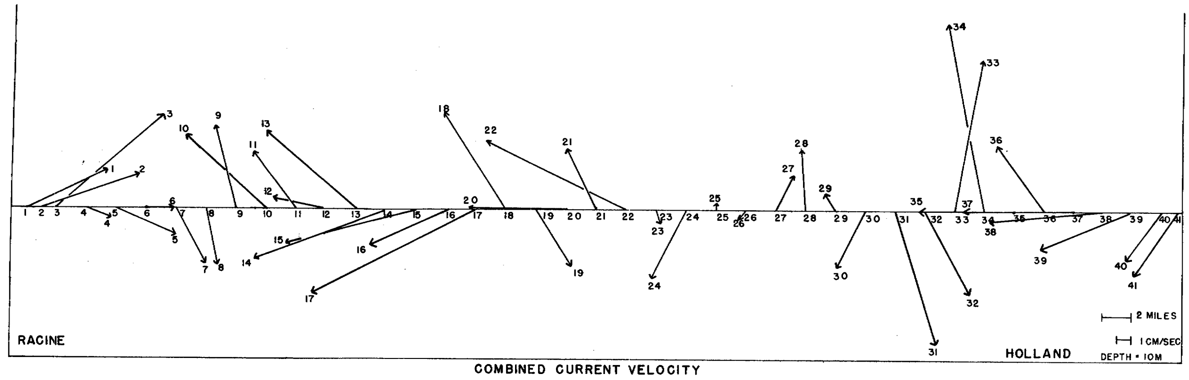
Fig. 18. Dynamic height currents calculated from 2-boat BT transect. November 1, 1965.



SURFACE TEMPERATURE TRANSECT INLAND SEAS NOVEMBER 1, 1965



CURRENT VECTORS COMPUTED BY METHOD OF DYNAMIC HEIGHTS INLAND SEAS NOVEMBER 1, 1965



COMBINED CURRENT VELOCITY

Fig. 18 concluded.

as the lake basin. Due to viscosity and internal shear stresses, it is suggested that there may be a spectrum of eddy sizes down to the quasi-molecular scale that we know as viscosity. It is therefore suggested that the basic circulation of a water mass is thermally generated, and that the primary pattern is related to the size of the basin. This suggestion may serve to explain the apparent variation of eddy viscosity and vorticity with the size of the basin.

The concept of a distribution of sizes of geostrophic vortices as a mechanism for energy exchange within the body of Lake Michigan appears to be supported by surface temperature profiles taken across the lake. These profiles show a general persistence of structural shape that varies slowly with the progression of the summer heating season. J. Verber (personal communication), the PHS Great Lakes-Illinois River Basins Project, has indicated that preliminary analysis of the monthly average current characteristics in Lake Michigan exhibits a seasonal progression of the current pattern. This may well be related to the changing thermal structure of the lake and to the relative efficiency of the air-sea coupling based on air-water temperature differences. The temperature dependence of the air-sea coupling as related to sea state in the spring and fall has been documented by Bellaire (1965) and Strong and Bellaire (1965).

The seasonal progession of surface temperature patterns is shown by the temperature transects in Figure 19. These data were obtained from a recording thermograph installed on the carferry CITY OF MADISON that crosses Lake Michigan between Muskegon and Milwaukee. The thermograph was installed by the Great Lakes Research Division, Project WP-00311. The temperature patterns through the summer season are illustrated by taking temperature transects at weekly intervals, beginning on 7 May and continuing through 26 November. The spring warming of the edges of the lake is clearly shown in the May and June transects, and the fall cooling is seen in the September, October, and November records.

The larger features of the temperature transects are remarkably persistent from week to week. The rather drastic changes during the weeks of 9-16 July and 23-29 July are attributed to sinkings and upwellings corresponding with strong frontal passages on 13 July and 24 July (Weatherwise, Vol. 18, No. 5, Oct. 1965, pp. 233-34). The records for the month of August are incomplete, due to the ship being temporarily laid up for shipyard maintenance.

The persistence of the large-scale temperature features gives credence to

the hypothesis that the circulation pattern may be defined by the thermal structure of the lake, rather than by a simple wind stress. The function of the wind stress in interpreted as being a source of energy for the maintenance of the rotation of the thermally-generated geostrophic eddies. Strong wind systems can cause sufficient mixing to make rather large perturbations of the temperature structure and thereby create a new circulation pattern.

If this argument is valid, there should be a persistence of the small-scale features of the surface temperature transects. Temperature records from successive crossings of the lake by the MADISON are shown for five periods in Figure 20. The MADISON's schedule varies slightly, but she makes a crossing of the lake at roughly 9-hr intervals. The temperature records for 15-18 June, 6-7 September, 9-15 October, 25-26 October, and 1-6 November are presented. Significant persistence of the fine-scaled structure of the temperature curves can be seen.

Ichiye (1965) has reported on observations of geostrophic eddies in the ocean, Stern (1965a, b; 1966) has done a theoretical study demonstrating conditions under which a geostrophic vortex will maintain a stable structure under the influence of a wind field, and has indicated a need for new concepts in the investigations of the turbulent energy dynamics of wind-driven circulations.

In a survey of sea surface temperature fluctuations with an airborne infrared thermometer, Alexander (1965) shows patterns of sea surface temperature fluctuations with a regularity of pattern that suggests a definable wave-length spectrum. These temperature fluctuations, together with accompanying photographs of lines of floating seaweed, support the concept of a distribution of various sizes of rotational feature in the surface currents.

Stern (1965a, b) has done a theoretical investigation which is generalized to include the special case of Charney (1955), which considers the interaction of a uniform wind stress with a geostrophic vortex. This work shows that the differential advection of geostrophic vorticity by the undisturbed Ekman component tends to tilt the axis of the vortex away from the vertical, but, because of the strong rotational constraint, the vortex maintains vertical "rigidity" by developing vertical velocities which balance the advective tendency (and frictional rotation). If the base of the mixed layer were rigid, the vortex would move as a unit with the velocity of the mean Ekman drift. In the approximate vorticity balance for a "frictional" component of the total motion, the vertical integral implies a net vertical velocity ("Ekman suction") at the free surface.

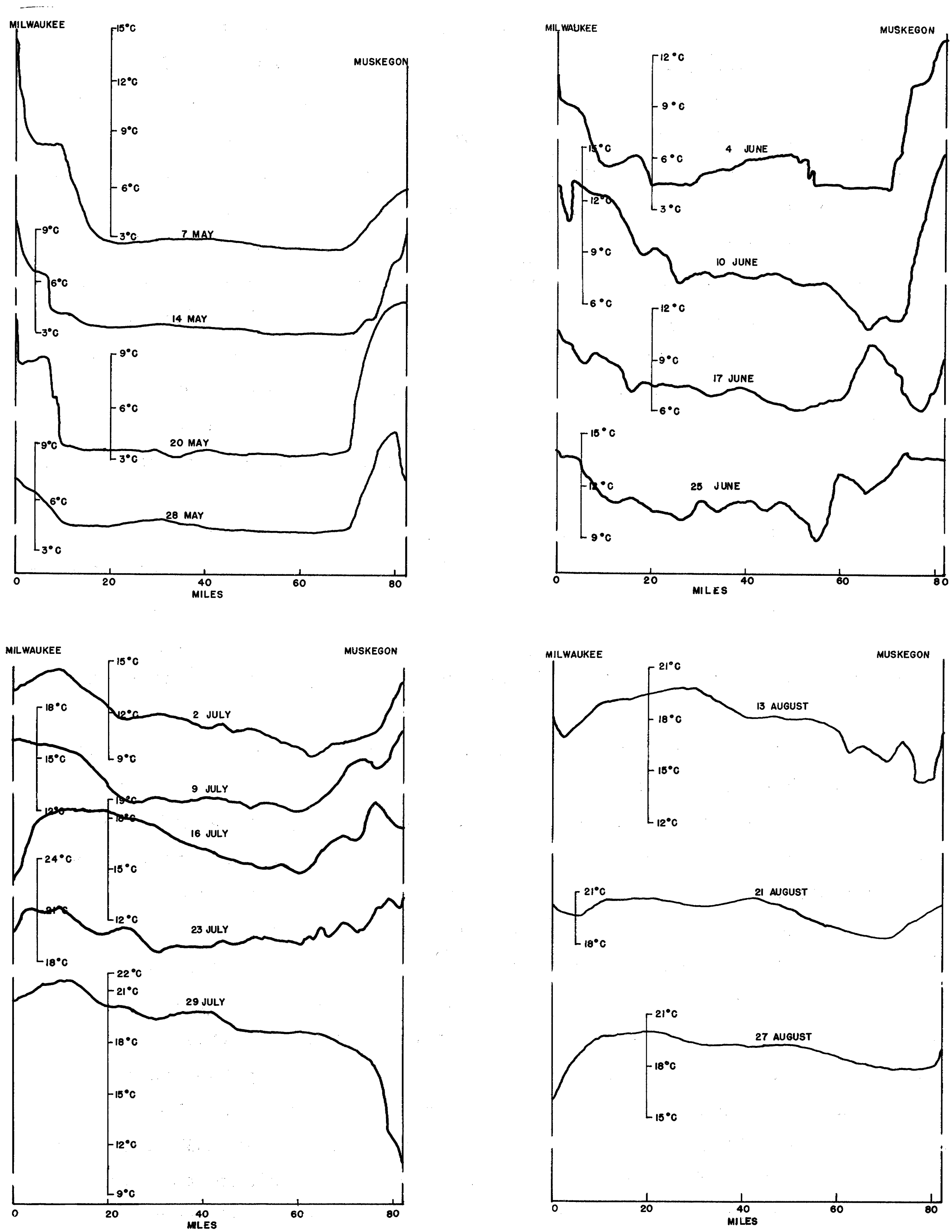


Fig. 19. Weekly surface temperature transects, Milwaukee-Muskegon, 1965.

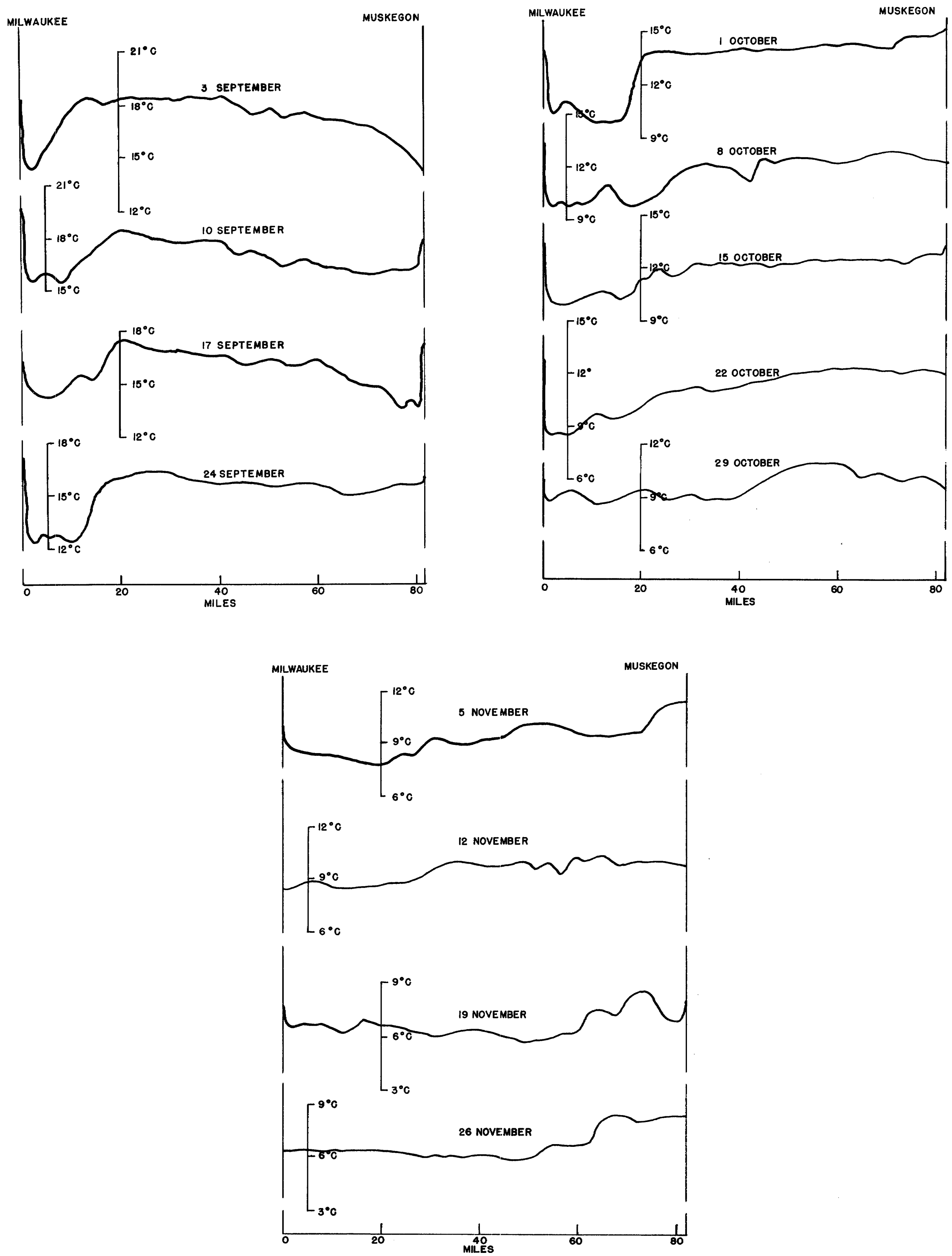


Fig. 19 concluded.

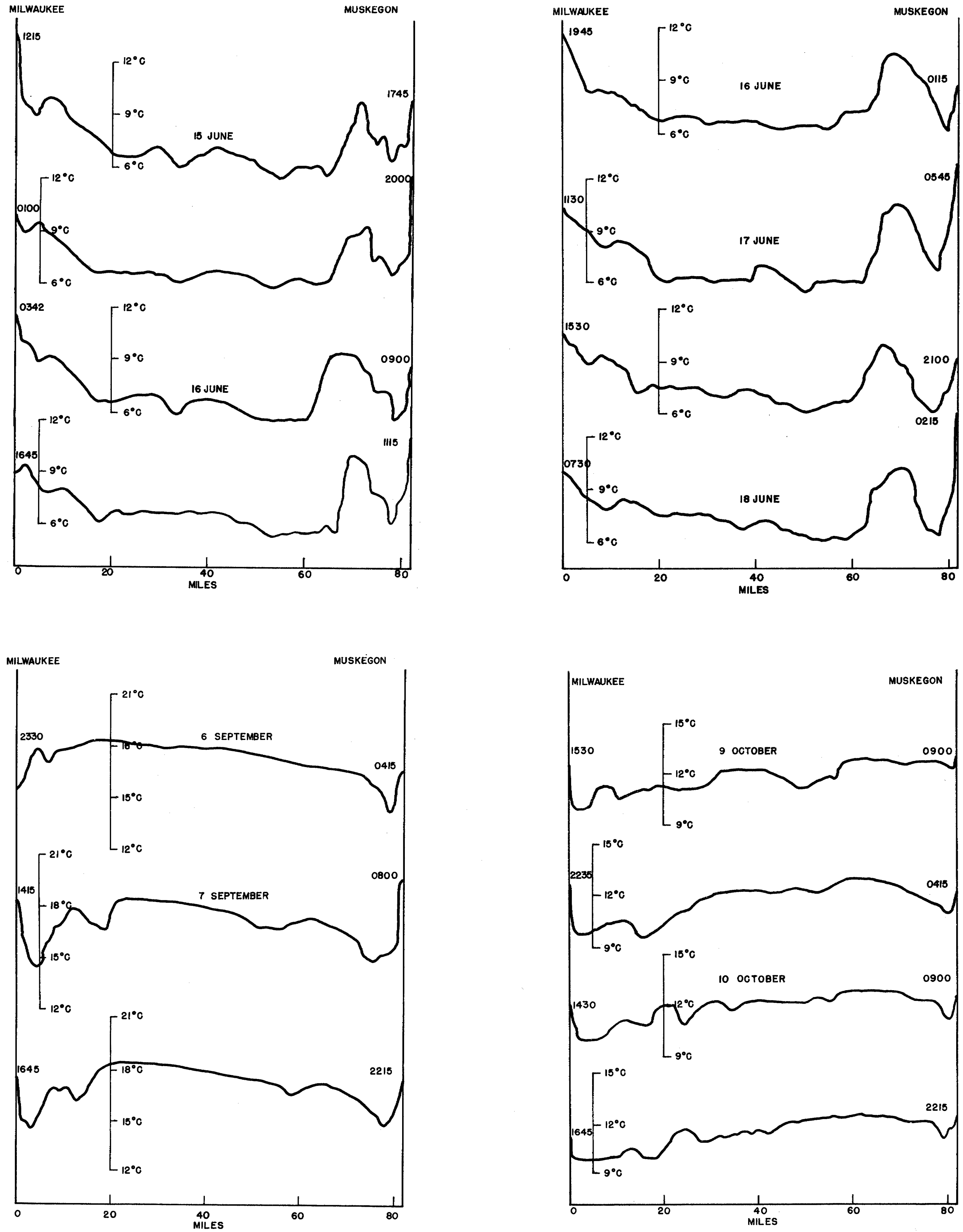


Fig. 20. Surface temperature transects from successive crossings of Lake Michigan by carferry CITY OF MADISON, Muskegon-Milwaukee, 1965.

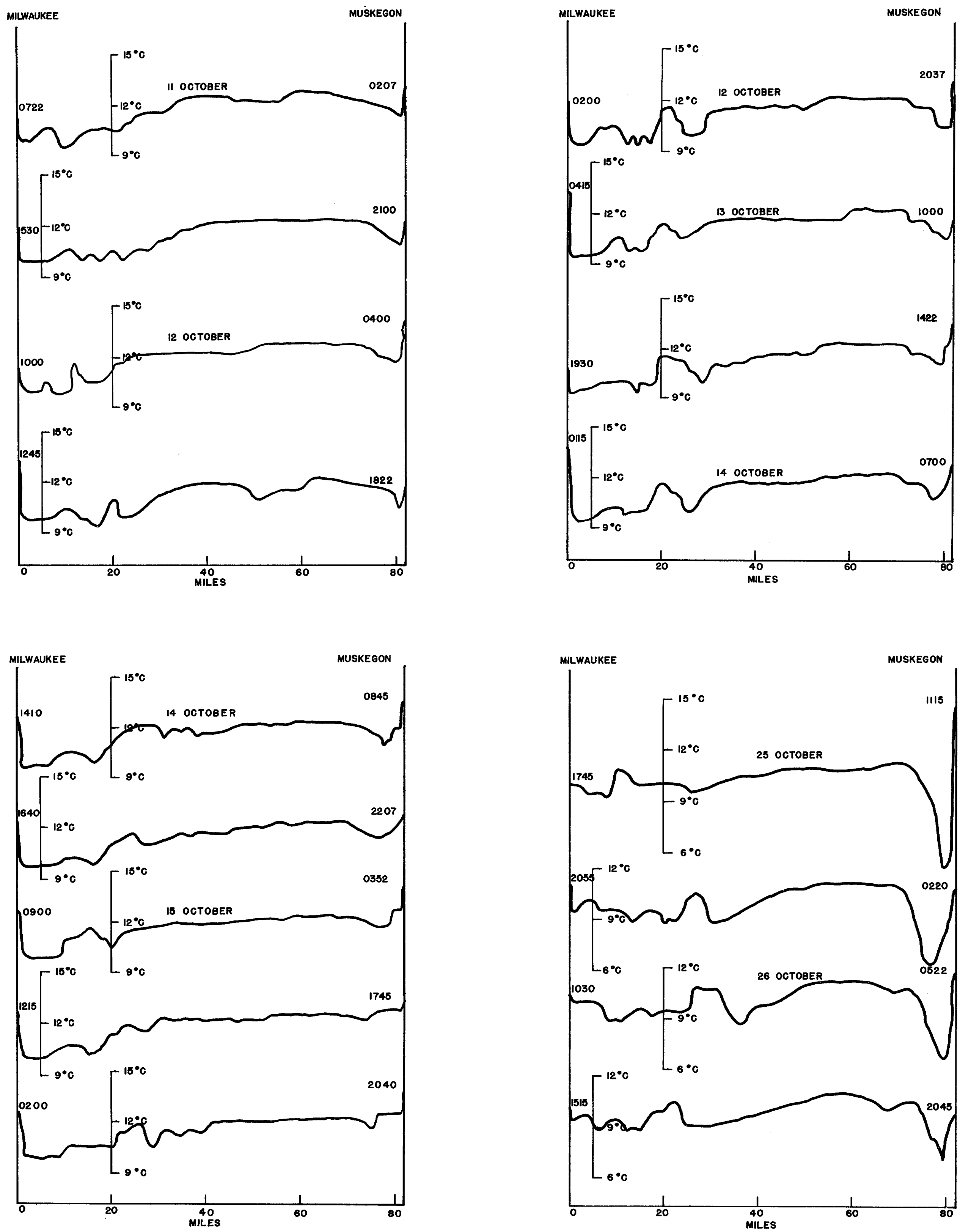


Fig. 20 continued.

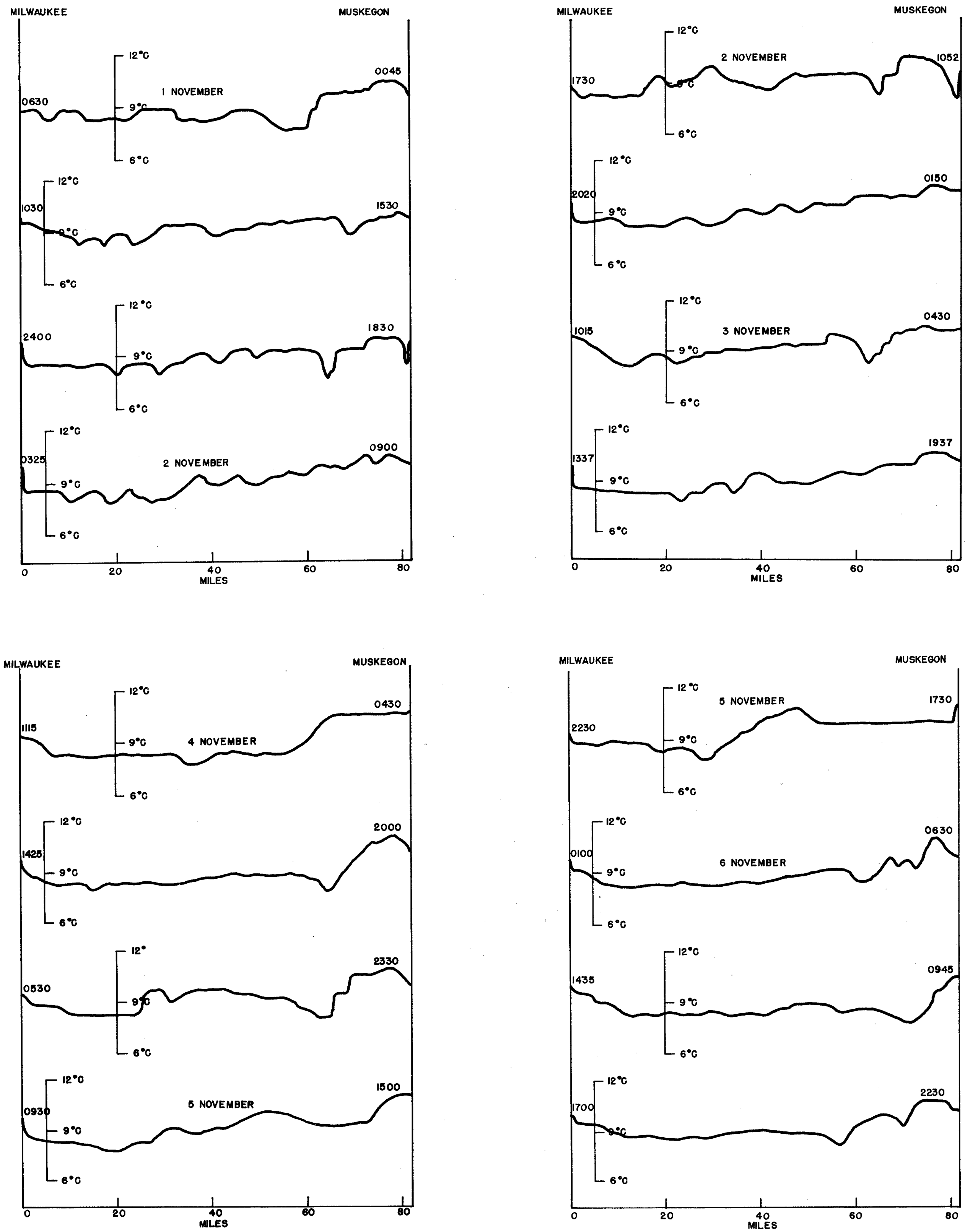


Fig. 20 concluded.

Applying Stern's model to a system of contra-rotating eddies, it is suggested that there would be a regular pattern of weak sinkings and upwellings at the centers of these eddies. It would therefore be expected to find a periodic fluctuation of the water surface temperature which would reflect the eddy structures.

Niiler, Robinson, and Spiegel (1965) have recently shown that the circulation of the North Atlantic basin may be reasonably well described on the basis of a 3-dimensional model of a thermohaline-maintained circulation for a closed basin.

Kirwan (1966) has just reported on an investigation of a theory of turbulent eddies which considers the significance of the Eulerian-Lagrangian transformation, and which distinguishes between turbulence induced purely by the mean vorticity and that associated with mean deformation. This leads to a distinction between two types of turbulent kinetic energies: one associated with the mean deformation of turbulent eddies, and one associated with the mean vorticity as exemplified by the average rotation of the eddies.

There may be a dominant size of eddy that contains most of the rotational kinetic energy which is defined by the shear stresses associated with the rotational speed and the water viscosity. The eddy sizes and rate of rotation would be expected to show a variation with the local wind stress. It was felt that the existence of a system of counter-rotating geostrophic eddies would be reflected in the periodicity of the temperature profile. The surface temperature profile from the INLAND SEAS on 1 November 1966 (Racine to Holland) was analyzed to obtain a wave-length spectrum of the temperature fluctuations.

The spectra obtained from the surface temperature transect of 1 November 1966 are shown in Figures 21-24. The water temperature was measured in the main suction line of the ship (about 6 ft below the water line), and recorded at 1-minute intervals. Figure 21 is the normalized spectrum of the data with the cross-lake trend removed. The spectra were computed using 25 lags which resulted in 37 degrees of freedom. The large amplitude of the spectrum at low wave-lengths masked the detail at the higher frequencies, so the temperature record was filtered using 10, 20, and 50 point filters and the spectrum was run again. The curves are shown in Figures 22-24. These filters are high-pass filters (low frequency cut-off) with 50% attenuation at 3.3, 2.5, and 1.5 miles wave-length respectively. The filtered spectra show a definite structure

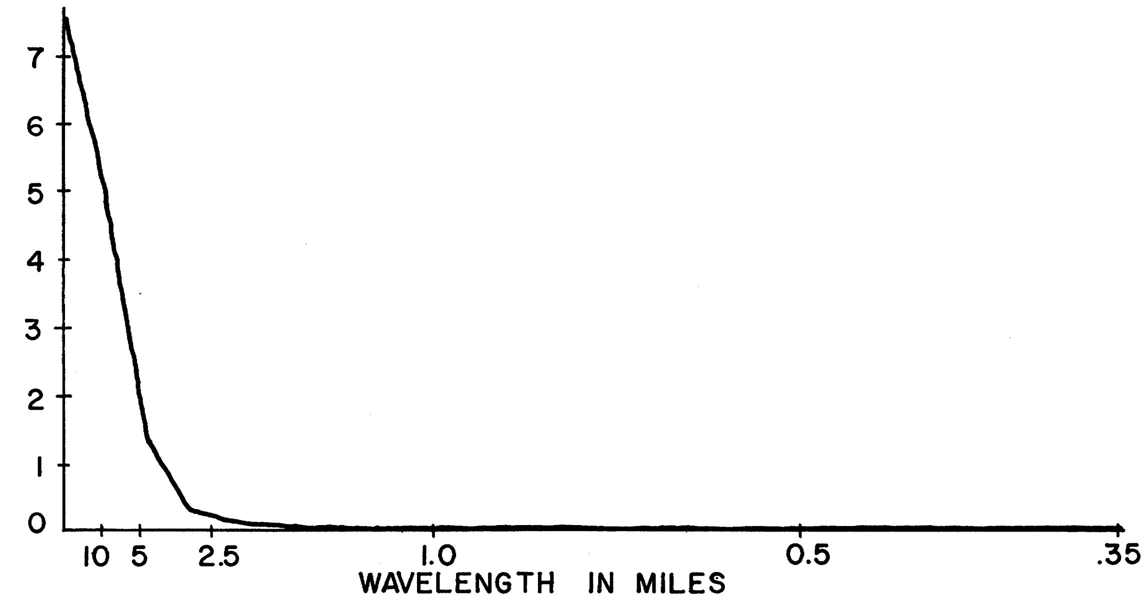


Fig. 21. Normalized spectrum of surface temperature fluctuations, Racine-Holland transect 1 November 1965.

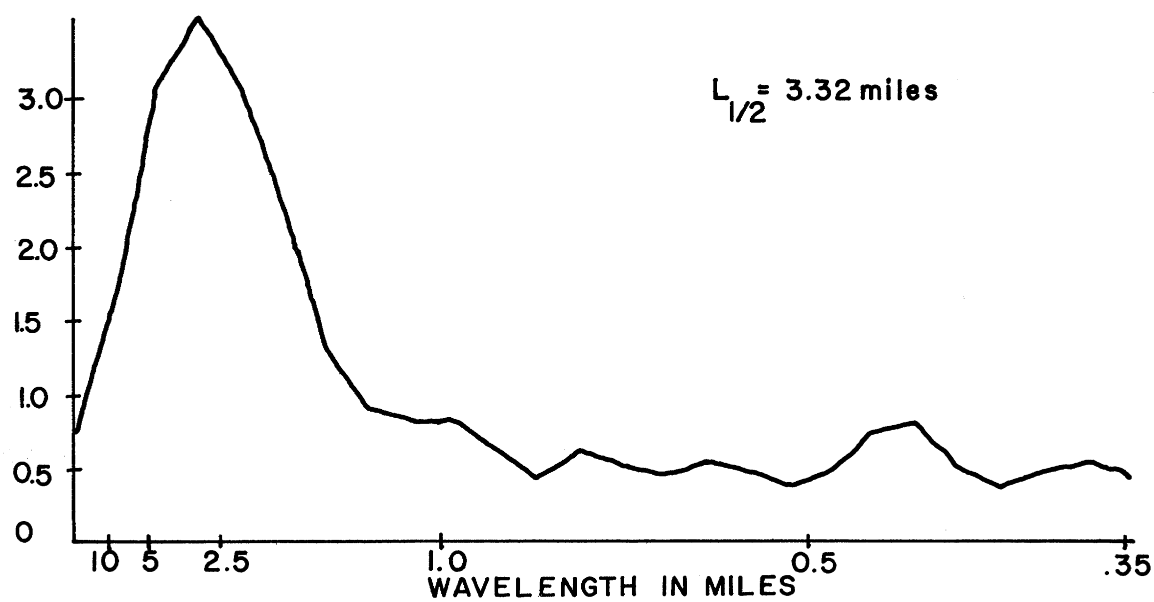


Fig. 22. Normalized spectrum of filtered surface temperature fluctuations, Racine-Holland transect 1 November 1965. Equivalent high-pass filter. Half-power wave-length 3.32 miles.

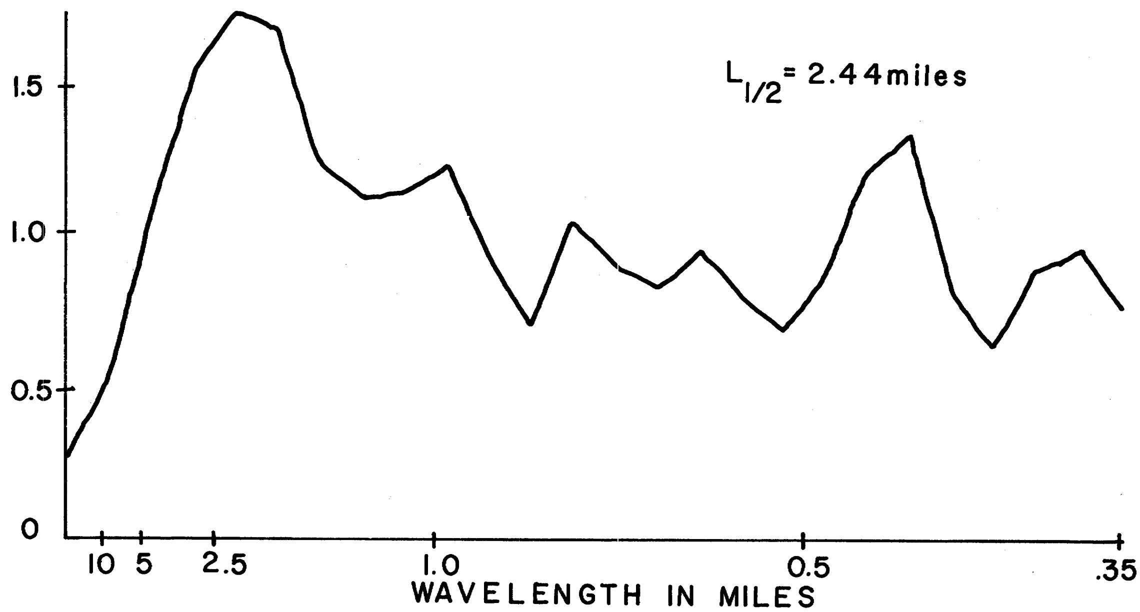


Fig. 23. Normalized spectrum of filtered surface temperature fluctuations, Racine-Holland transect 1 November 1965. Equivalent high-pass filter. Half-power wave-length 2.44 miles.

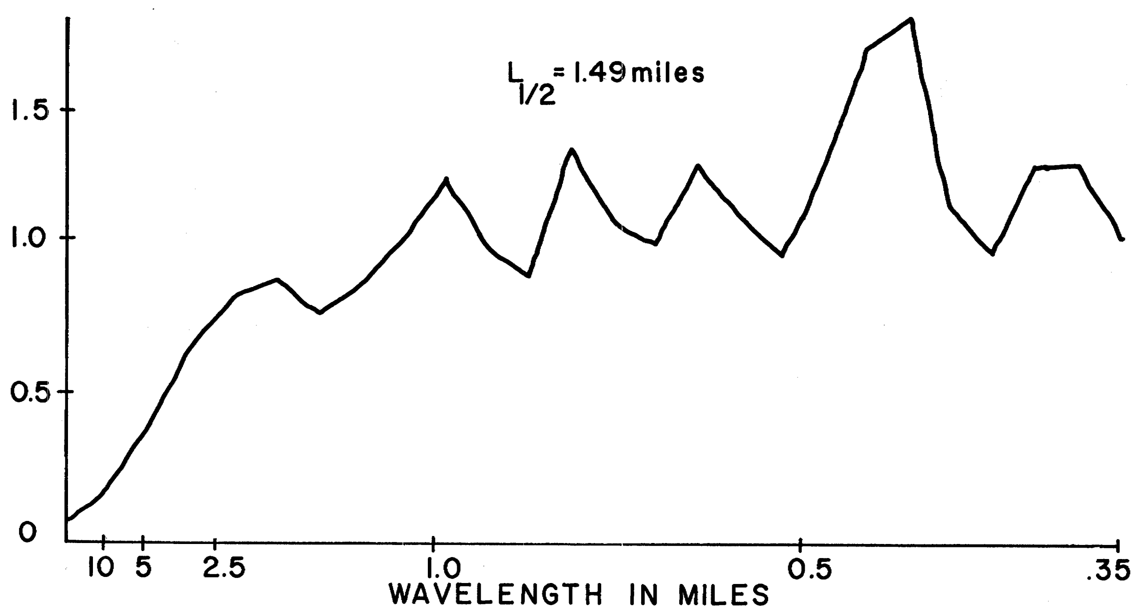


Fig. 24. Normalized spectrum of filtered surface temperature fluctuations, Racine-Holland transect 1 November 1965. Equivalent high-pass filter. Half-power wave-length 1.49 miles.

at the shorter wave-lengths, which may indicate the existence of geostrophic eddies.

The hypothesis that has evolved from this research program is, obviously, an over-simplification of the complex mechanism of circulation dynamics. These experimental observations have, however, indicated a new line of attack upon circulation problems, and have established the validity of an impirical area for verification of theoretical models such as are now being proposed by Stern and Niiler et al. It is anticipated that this program shall be continued and that the Great Lakes may provide a laboratory for the synoptic determination of a basin circulation in order to more fully develop the theoretical modelling and conceptual understanding of circulation dynamics.

ACKNOWLEDGMENTS

The work done under this grant (WP 00794-01) is largely a theoretical study. The investigations have been conducted in close cooperation with Dr. J. C. Ayers' Coherent Area program, (WP-00311). The interrelationship between the two projects has provided the necessary mechanism for supplying additional experimental data as required, and for carrying out definitive field measurements for testing of the theoretical hypotheses. The results of this study are subsequently applied in the brodened measurements program carried out within the Coherent Area operations.

The author is indebted to the U. S. Public Health Service (now Federal Water Pollution Control Administration) Great Lakes-Illinois River Basins Project for the data from Buoy Station 8, and to Fred V. Brock of the Meteorology and Oceanography Department, University of Michigan, for his assistance and direction of the computer applications for this project.

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